PRACTICAL HEAT

TERRELL CROFT, Editor

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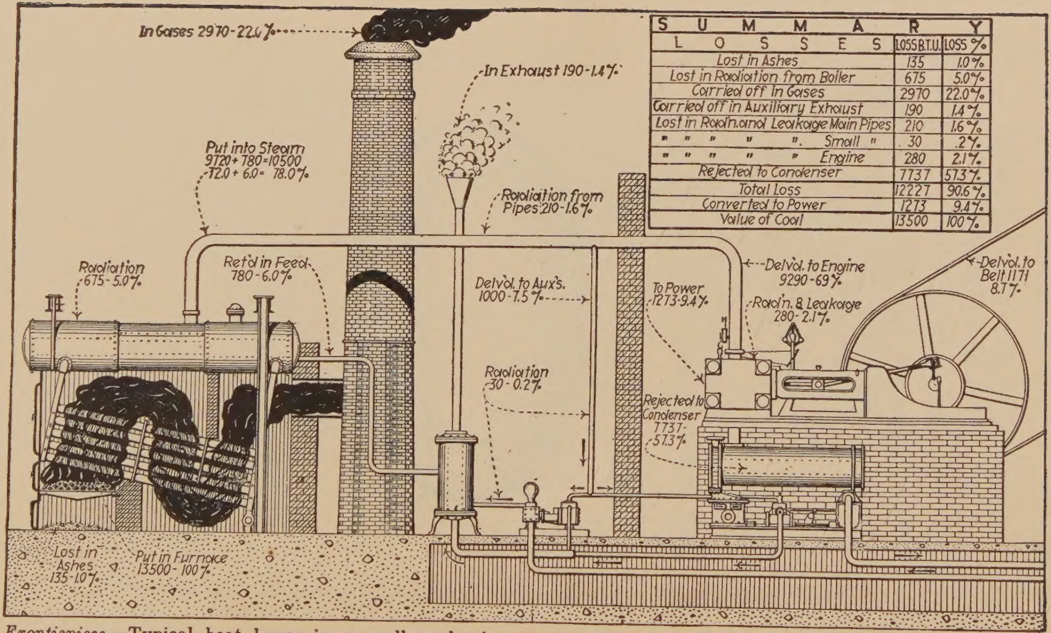

S U M M A R Y		
L O S S E S	LOSS B.T.U.	LOSS %
Lost in Ashes	135	1.0%
Lost in Radiation from Boiler	675	5.0%
Carried off in Gases	2970	22.0%
Carried off in Auxiliary Exhaust	190	1.4%
Lost in Rad'n. and Leakage Main Pipes	210	1.6%
" " " " ". Small "	30	.2%
" " " " " Engine	280	2.1%
Rejected to Condenser	7737	57.3%
Total Loss	12227	90.6%
Converted to Power	1273	9.4%
Value of Coal	13500	100%

Frontispiece.—Typical heat losses in a small condensing steam power plant. (The "*Loss B. T. U.*" column indicates the loss in British thermal units per pound of 13,500-B. t. u. coal burned.)

PRACTICAL HEAT

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CONSULTING ENGINEER. DIRECTING ENGINEER, TERRELL CROFT ENGINEERING CO.
MEMBER OF THE AMERICAN INSTITUTE OF ELECTRICAL ENGINEERS.
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MEMBER OF THE ILLUMINATING ENGINEERING SOCIETY.

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PREFACE

PRACTICAL HEAT endeavors to live up to its title. It endeavors to be just what its title indicates. It is a book on heat, and the practical applications of heat, which may be intelligently followed by persons of limited mathematical attainments—a working knowledge of arithmetic should suffice. Matters of theoretical interest only have been avoided. While it is emphasized that this is a "practical" book, it should not be inferred that theory has been ignored. On the contrary the entire work has been planned on the basis of this fact; that one cannot really understand the practical or application features of any subject, unless he is familiar with the fundamental theory of the subject.

So, in *Practical Heat* great care has been exercised in the preparation of its earlier divisions to establish firmly these fundamental principles which underlie all heat phenomona. But in establishing these principles the controlling policy has been to present all ideas in such a way that they can be readily understood by those of limited education. While simplicity has been the keynote, technical accuracy has never been sacrificed. Hence, the book should also prove useful to any reader —regardless of the excellence of his previous education—who desires an accurate easily-assimilated treatment of the subject.

Drawings for all of the illustrations were made especially for this work. It has been the endeavor to so design and render these pictures that they will convey the desired information with a minimum of supplementary discussion.

Throughout the text, principles which are presented are explained with illustrated descriptive expositions or with worked-out arithmetical examples. At the end of each of the 19 divisions there are questions to be answered and, where justified, problems to be solved by the reader. These questions and problems are based on the text matter in the division just preceding. If the reader can answer the questions and solve the problems, he then must be conversant with the subject

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matter of the division. Detail solutions to all of the problems are printed in the appendix in the back of the book.

As to the method of treatment: Force, pressure, work, energy, and power, are first considered because they are fundamental concepts upon which all physical science is founded. Next follows a discussion of the nature of heat, its basic significance, its one source, and its relation to matter and temperature.

Succeeding this, in the division on *Heat Its Measurement And Transformations*, the fundamental laws of heat phenomena, such as the first law of thermodynamics, the second law of thermodynamics, and the fundamental heat-transfer equation are expounded in a simple manner. Upon the principles and laws which are stated in this division (and which are more fully developed in the succeeding divisions) are based all practical engineering processes.

The effects of heat, such as the expansion and contraction of solids and liquids, the heat phenomena of gases, the melting and freezing of substances, vaporization, and the properties of vapors are then examined. In the division on the *Heat Phenomena Of Gases* it has been the endeavor to so treat this rather theoretical subject that the practical man—or one with little mathematical training—can readily understand it.

Following this discussion of the effects of heat, gas and vapor cycles are introduced—since the principles involved therein form the ground-work of all practical heat-engine and heat-power-plant design. In the next division the subjects of combustion, fuels, steam power plants, internal-combustion-engine power plants, building warming, and refrigeration are given space, as they are the practical *applications* of heat phenomena. In these "application" divisions the aim has been to demonstrate how the principles which were developed in the preceding divisions are employed in practical heat engineering. Finally, a division on instruments is included. In this are shown the various instruments which are employed in heat engineering; their purposes, usefulness and limitations are examined.

With this, as with other books which have been prepared by the author, it is the sincere desire to render it of maximum usefulness to the reader. It is the intention to improve the book each time it is revised and to enlarge it as conditions may demand. If these things are to be accomplished most effectively, it is essential that the readers cooperate. This they may do by advising the author of alterations which they feel would be desirable. Future revisions and additions will, insofar as is feasible, be based on such suggestions and criticisms from the readers.

Although the proofs have been read and checked very carefully by a number of persons, it is possible that some undiscovered errors may remain. Readers will confer a decided favor in advising the author of any such.

TERRELL CROFT.

UNIVERSITY CITY,
ST. LOUIS, MO.,
February, 1923.

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The editor desires to here acknowledge the assistance which has been rendered by various concerns and individuals in the preparation of this book.

Among the companies which have cooperated are the: *H. K. Porter Co., Pittsburgh, Pa.; Central Scientific Co., Chicago, Ill.; American Radiator Co.; Harrison Safety Boiler Works; Buck Stove & Range Co., St. Louis, Mo.; Westinghouse Machine Co., East Pittsburgh, Pa.; Vilter Mfg. Co.; Henry Vogt Machine Co.; Taylor Instrument Co., Rochester, N. Y.; Defender Automatic Regulator Co., St. Louis, Mo.*

Furthermore, certain of the text material appeared originally as articles in certain trade and technical periodicals among which are: *Power, Combustion, Southern Engineer, and Power Plant Engineering.*

Numerical values for tables and graphs have, in certain instances, been taken from engineering textbooks of recognized high standing. In such cases acknowledgment is made at the place where the values are used.

Special acknowledgment is hereby accorded Edmond Siroky, Head Mechanical Engineer of The Terrell Croft Engineering Company, who has been largely responsible for the technical accuracy of the book, who prepared or supervised the preparation of considerable of the manuscript and who has originated and assisted throughout in many valuable ways.

Other acknowledgments have been made in different places in the book. If any has been omitted it has been through oversight and, if brought to the editor's attention, it will be incorporated in the next edition.

TERRELL CROFT.

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PRACTICAL HEAT

DIVISION 1

FORCE, PRESSURE, WORK, ENERGY, POWER

1. Such Terms As "Force," "Work," "Energy," And "Power" Are Discussed At The Outset because an understanding of their technical significance is essential to the intelligent study of heat and its effects. As the reader proceeds, it will be shown that *heat is energy.* Furthermore, *energy is stored work* and *work is force multiplied by distance.* If the student is thoroughly familiar with these ideas he need not, necessarily, read Div. 1. But probably, in any case, a review will be profitable.

2. A "Force" Is A Push Or A Pull; this is the technical meaning of the word force. That is, a force is anything which has a tendency either to impart motion to a body which is at rest, or to change or destroy the uniformity of the motion of a moving body. A force may be due to an attraction or a repulsion. Also, not only may a condition of rest or motion be altered by a force but the body itself may be altered thereby. It may be stretched, compressed, twisted, or bent.

Example.—If a force is applied to a stationary body, the body then moves or tends to move. If the body is already in motion, its speed or its direction of motion will be changed by the application of the force. Or, possibly, both its speed and its direction may be changed. The speed may be increased or decreased, depending on whether the force assists or opposes the motion.

Example.—The most common force is that due to gravity. It is called weight. If a thing weighs 10 lb., this means that the earth pulls on it with a 10-lb. force. Steam exerts force on an engine piston. Internal steam pressure exerts force on the bolts in a flanged pipe union. The bolts exert a restraining force.

3. The "Pound" Is A Unit For Measuring Force.—A properly calibrated spring balance (Fig. 1) will indicate the magnitude of a force in pounds. Other weighing devices may sometimes be used to determine the magnitudes of forces. Although units other than the *pound*—such as the "ounce," "gram," "ton" and "kilogram"—can be used for measuring forces, the "pound" is the one which will be employed most often in this book.

Note.—In Practically All Research Work, And Altogether In Europe, Great Britain Excepted, Metric Units Are Used for measuring forces and weights. The *gram* is the metric-system unit of force and weight. The *kilogram*, a larger unit, is 1,000 grams. See Table 4.

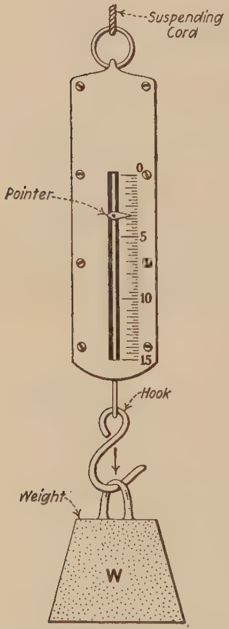


Fig. 1.—Weight is force due to gravity; the spring balance reads 3¼ lb.

Example.—Figure 1 illustrates the force of gravity. Gravity is pulling the weight, **W**, down with a force of 3¼ lb. Opposing the downward pull, the spring in the balance is pulling up with a force of 3¼ lb. Thus here, as always, there are two equal and opposite forces.

Example.—In Fig. 2, the spring balance is measuring pulling forces. Note that there are two opposing 10-lb. forces. One is exerted by each hand. These two forces must be equal and opposite.

Example.—To move a freight car (Fig. 3) along a track, a force, *P*, must be applied. This force, or draw-bar pull, is necessary to overcome the friction of the wheels on the track, that of the axles in the bearings, and the resistances due to wind pressure and inertia. The sum of these opposing forces must be equal and opposite to the draw-bar pull. If, in some manner, the friction be decreased, the force of 625 lb. will be more than sufficient to pull the car at the speed at which it had been traveling. The excess force will then become effective in overcoming the inertia of the car. Thus, the car's speed will be increased until the wind and other resistances become sufficiently great that the 625-lb. draw-bar pull is just counterbalanced by them; then again the car will be drawn along at a constant though greater speed.

Note.—The Difference Between Weight And Mass should be understood. *The mass of a body is that which remains unchanged in all the transformations which the body may undergo. The weight of a body is the gravitational force or pull which is exerted on the body by the earth.* The weight of a body is different at different points on the earth; on a mountain peak its weight will be less than at sea level. Were the body carried (if possible) to the center of the earth, its weight there would be zero. But its mass is independent of its position. The standard or unit of mass is (in the English system) the *pound mass* which is the amount of mass in a certain lump of metal that is carefully preserved in London. The unit of weight is the *pound force* which is the force required to support the standard pound (mass) body at sea level and 45 deg. latitude. *Weights are indicated by spring balances; masses are indicated by platform balances.* Thus, if a pound mass were supported by a spring balance and carried to different elevations, the balance would show different weights for the same substance—if it were carried to the center of the earth it would read zero. But, if a pound mass were balanced on a platform scale against another equal mass, the two masses would balance at all points on or in the earth.

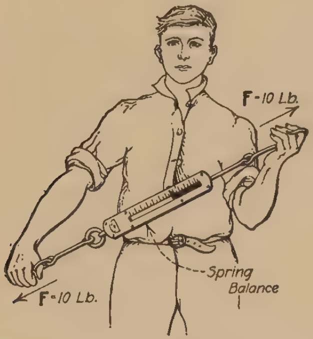

F-10 Lb.
Spring Balance
F-10 Lb.

FIG. 2.—Force due to a pull; the spring balance reads 10 lb.

FIG. 3.—Draw-bar pull (force) on freight car.

It is a fact, however, that the weight of a body for different places on the earth's surface varies, between the extremes, by only about ½ per cent. Hence, for all practical purposes, it may be assumed that the weight of a body is a measure of its mass. In this book, therefore, no distinction will, in general, be drawn between the mass of a body and its weight. The "pound" will be used to mean both "pound mass" and "pound weight."

4. Table Showing Relation of Metric-system to English-system Units Of Force Or Weight.—The English ton here tabulated is the "short" ton as used in the United States. In Great Britain the "long" ton (2,240 lb.) is used instead.

	Units	English			Metric		
		Ounce	Pound	Ton	Gram	Kilogram	Metric ton
English	1 oz. =	1	$\frac{1}{16}$ = 0.062,5	$\frac{1}{32,000}$ = 0.000,031,25	28.35	0.028,35	0.000,028
	1 lb. =	16	1	$\frac{1}{2,000}$ = 0.000,5	453.6	0.453,6	0.000,454
	1 ton =	32,000	2,000	1	907,200	907.2	0.907,2
Metric	1 gram =	0.035,3	0.002,2	0.000,001,1	1	$\frac{1}{1,000}$ = 0.001	$\frac{1}{1,000,000}$ = 0.000,001
	1 kilogram	35.27	2.205	0.001,1	1,000	1	$\frac{1}{1,000}$ = 0.001
	1 metric ton =	35,273.6	2,204.6	1.102	1,000,000	1,000	1

EXAMPLES.—1 *oz.* = 28.35 *grams.* Also 1 *ton* = 907,200 *grams.* Again, 1 *lb.* = 16 *oz.* = 0.000,5 *ton* = 0.453,6 *kilograms*, etc.

5. "Pressure" Is Force Per Unit Area, as the word is used in a technical sense; note that its technical meaning is different from its general meaning. If two substances are in forceful contact, the surface of contact of each substance forces or holds back the contact surface of the other. The *intensity of the force* at any point on the contact surface *is called the pressure.* If two solids (Sec. 50) are pushed against each other with a force and if, Fig. 5, the areas of contact are perfectly smooth plane surfaces, the force between the two solids is assumed to be of equal intensity throughout the entire area of contact. That is, each unit area of the contact surface is assumed to take its share of the total force between the two bodies. The force sustained by each unit area is called the *pressure* of contact. Now when a *fluid* (a liquid or a gas) is confined within a container, it will take the shape of the container—a liquid will contact with the sides and bottom of the container; a gas will contact with all of the interior surfaces of the container. The fluid will then exert a force against the container at every contact point. The intensity of the force at any point is called the pressure at that point.

Note.—The Term "Pressure" is Generally Used Only For Fluids because it is doubtful whether the intensity of force between solids is ever uniformly distributed over the contact area as was assumed above. There are certain kinds of solids, however, which behave somewhat as do liquids and for which the term pressure is also often used—sand, soil, crushed rock, and similar finely divided substances are examples of such solids.

6. Fluid Pressure At Any Point Is Equal In All Directions.—It is proved in text-books on physics that the same force is exerted upward, downward, or sideways upon a small area which is so moved about within a fluid medium that its center is always at the same point. This may be explained by the perfect freedom of movement of the particles (molecules, Sec. 50) of a fluid among one another. One particle of the fluid exerts the same force on the particles above, to the right, to the left, and (except for its own weight which is so very small) below it. Hence, the fluid pressure at any point is equal in all directions. At different points, however, the fluid pressures may be widely different. At any point the fluid pressure depends on the height and nature of all fluids which are so situated above that point that they may produce pressure at that point. How fluid pressures are produced is explained below.

Explanation.—Imagine a huge square shaft or stack, *AB* Fig. 4, to extend from the bottom of a deep sea to the height of 60 miles above sea-level. Above this height we may assume that there is no air or atmosphere. Hence, above the plane *A* there is nothing that could press down on the plane *A*. Between plane *A* and plane *C*, however, exist a few particles, let us say, of the lighter gases which compose our atmosphere. These particles are attracted to the earth by gravity. Hence, they push downward on the plane *C*. Therefore, each square inch or other unit area which goes to make up plane *C*, is subject to a force or pressure. Between planes *C* and *D* are more particles than between *A* and *C*—because of the compressibility of gases. Hence, there is a greater downward push on plane *D* than on plane *C*. Therefore, each square inch, say, of plane *D* sustains a greater force than does each square inch of plane *C*—that is, the pressure at *D* is greater than that at *C*. The pressures on like planes below *D* would thus be greater as they are taken nearer to the sea-level. Thus the force acting downward on plane *E* is due to the weight of the gases in *AE*. Likewise at *S* (sea-level), the force pressing downward on the surface of the water would be that due to the total column of atmosphere *AS*. Each unit area of *S* would have to sustain its share of the weight of the gases in *AS*. The variations of atmospheric pressure are given in Sec. 9.

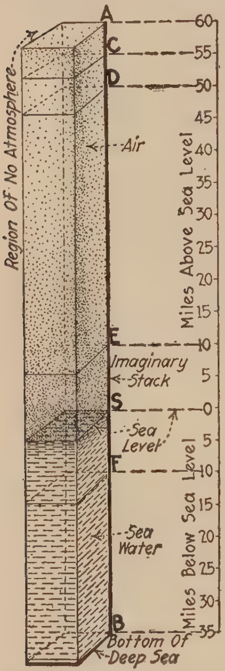


Fig. 4.—Illustrating why fluids exert pressure.

If, now, we consider a plane *F* at some distance below sea level, we find that there is acting down on this plane the weight of the water in *SF* besides the weight of the air in *AS*. The maximum pressure in the column would occur at the bottom plane *B* which is subject to the weight of all water in *SB* together with the weight of all of the air in *AS*.

To summarize, it may be said that *the deeper or higher the fluid column above a point and the greater the density of the fluid, the greater will be the pressure at that point.*

7. The Units In Which Pressures May Be Expressed are many. Since pressure is force per unit area and since forces may be measured in pounds, tons, and the like and areas may be measured in square inches, square feet, and the like, we have such pressure units as *pounds per square inch, pounds per square foot, tons per square foot,* and others. Furthermore, since any given pressure may be considered as the equivalent of that due to a liquid column of a certain height, it follows that pressures may be expressed in terms of liquid-column height. Hence, we have such pressure units as *inches of mercury column, feet of water column,* and others. The relations of the various pressure units are given in Table 19 and Sec. 18.

8. The Numerical Expression Of A Pressure is, as explained above, obtained by dividing *the total force which produces the pressure* by *the number of area units in the surface* over which the total force is uniformly distributed. This form of expression ordinarily assumes that the force is distributed uniformly over a contact surface. Hence the formula:

$$P = \frac{\mathbf{W}}{A} \qquad \text{(pressure)} \tag{1}$$

Wherein: P = the pressure, expressed numerically in the given unit of weight per assumed unit of area. $\mathbf{W}$ = the total load or force, expressed in any assumed unit of weight, which is applied to produce the total load or force. A = the total surface, expressed in any desired unit of area, whereon the total force is uniformly distributed.

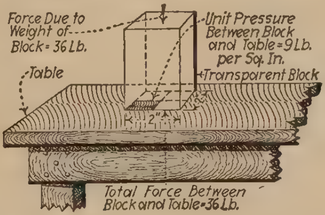

Force Due to Weight of Block = 36 Lb.
Unit Pressure Between Block and Table = 9 Lb. per Sq. In.
Table
Transparent Block
2"
2"
Total Force Between Block and Table = 36 Lb.

FIG. 5.—Illustrating "force" and "pressure" in terms of pounds and square inches.

NOTE.—If, in For. (1), $\mathbf{W}$ = pounds and A = square inches, then P = pounds per square inch. Also, if $\mathbf{W}$ = tons and A = square feet, then P = tons per square foot. And so with other combinations of the units of weight and area.

NOTE.—If the total non-uniformly distributed force which is imposed on a surface, is divided by the area of the surface then, the result will be the *average pressure.*

Example.—A certain 36-lb. block (Fig. 5) imposes a load or force of 36 lb. on the area upon which it rests. This area is 2 × 2 = 4 *sq. in.* Hence, by For. (1), the average pressure exerted by the block $= P = W/A = 36 \div 4 = 9$ *lb. per sq. in.*

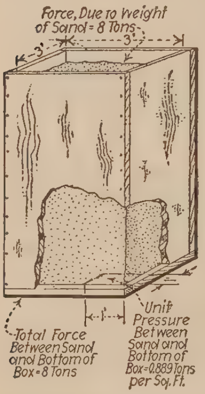

Force, Due to Weight of Sand = 8 Tons
3'
3'
Total Force Between Sand and Bottom of Box = 8 Tons
Unit Pressure Between Sand and Bottom of Box = 0.889 Tons per Sq. Ft.

Fig. 6.—Illustrating "force" and "pressure" in terms of tons and square feet.

Example.—A quantity of sand (Fig. 6) is poured into a box which is 3-ft. square inside. Thus the box has a bottom area of 3 × 3 = 9 *sq. ft.* The sand weighs 8 tons. Hence, the total load or force which it imposes on the bottom of the box is 8 tons. Then by For. (1), the pressure which the sand imposes $= P = W/A = 8 \div 9 = 0.889$ *ton per sq. ft.*

9. Atmospheric Pressure (Sec. 6) is the pressure which is exerted by the earth's atmosphere. This atmosphere extends for a great, though unmeasured, distance (Fig 7) above and enshrouding the earth's surface. The depth of the earth's atmosphere has been estimated by different experimenters; the estimates range from 30 to 212 miles. This atmospheric pressure varies, according to the altitude, above sea-level, of the place at which the pressure is measured. At sea-level the atmospheric pressure at a temperature of 32° F. is, so tests

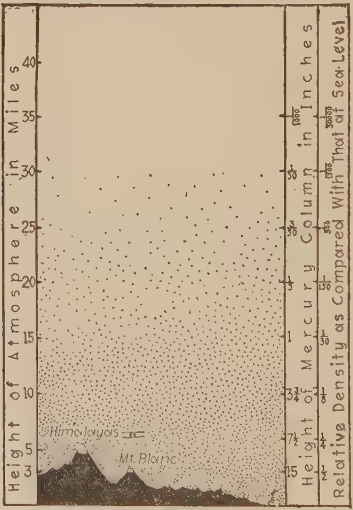

Height of Atmosphere in Miles
40
35
30
25
20
15
10
5
3
Himalayas
Mt. Blanc
Height of Mercury Column in Inches
1
3¾
7½
15
Relative Density as Compared With That of Sea-Level

Fig. 7.—Showing how atmospheric pressure decreases as the height above the earth increases.

show, about 14.7 lb. per sq. in. That is, *a column of air, which has a cross-sectional area of* 1 *sq. in. and which extends from sea-level to the upper limit of the earth's atmosphere, weighs* 14.7 *lb.*, or more exactly 14.696 *lb.* Thus we are (at sea-level) existing with a pressure of 14.7 lb. per sq. in. which is imposed by the fluid in which we live on all portions of our bodies. The same pressure is imposed on all things which are about us. But we are, ordinarily, unaware of the existence of this imposed pressure in the same way that a fish is, probably, unaware of the existence of the water in which it lives.

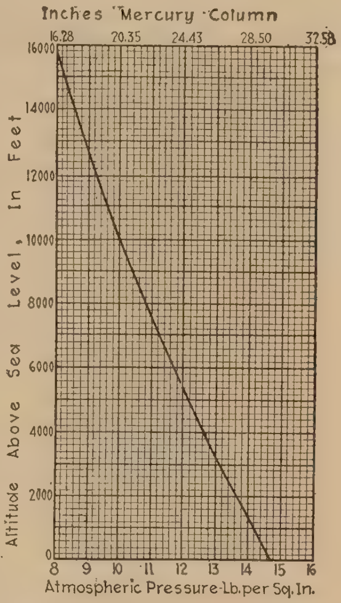


Fig. 8.—Variation of atmospheric pressure with altitude. (Due to the compressibility of air, the pressure does not decrease directly with the height above the sea-level. Hence the graph is not a straight line.)

Note.—The Decrease Of Atmospheric Pressure With Increase In Altitude (Fig. 8) is due to the fact that the depth of the atmosphere above an observer grows less as his altitude grows greater. The atmospheric depth above a man in an airplane 2 miles above sea-level is 2 miles less than the atmospheric depth above a man standing on the ground at sea-level. The man at sea-level is under the pressure—14.7 lb. per sq. in.—due to the full depth of the atmosphere. The man in the airplane is relieved of the pressure due to the 2-mile depth of atmosphere beneath him and therefore (Fig. 8) the atmospheric pressure imposed on him is only about 9.6 lb. per sq. in.

10. Atmospheric Pressure Can Be Measured With A Barometer (Figs. 9 and 10). The barometer is an instrument which operates upon the principle (Fig. 11) of equilibrium between the weight of a column of mercury and the weight of a column of atmospheric air (Fig. 4) of the same cross-sectional area. Pressure which is read on a barometer is called *barometric pressure or barometer reading*.

Explanation.—A glass or porcelain dish (Fig. 12) contains a quantity of mercury, *M*. A 3-ft. (or longer) glass tube, closed at one end and having an inside diameter of any size, is filled with mercury. The thumb (Fig. 12-*I*) is held over the open end of the tube. The tube is then inverted. The open end of the tube, still covered by the thumb, is now thrust beneath the surface of the mercury in the dish. The thumb is then removed. With the tube held vertically, the column of mercury therein will now fall away from the closed end. The

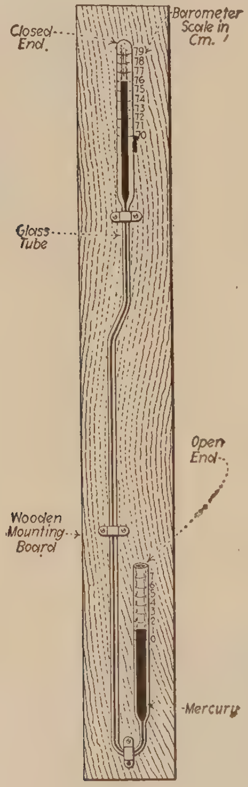


Fig. 9.

Fig. 9.—Simple mercury barometer.

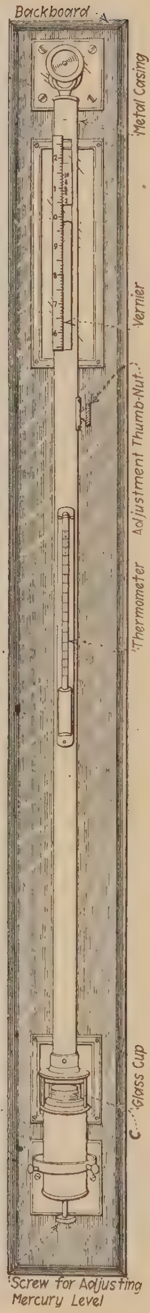


Fig. 10.—Laboratory barometer (for every observation, the level of the mercury in cup *C* must be adjusted accurately to the tip of an ivory point, within *C*, which is not shown).

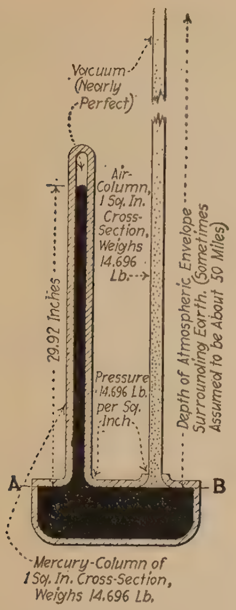

Vacuum (Nearly Perfect)
Air-Column, 1 Sq. In. Cross-Section, Weighs 14.696 Lb.
29.92 Inches
Depth of Atmospheric Envelope Surrounding Earth. (Sometimes Assumed to be About 50 Miles)
Pressure 14.696 Lb. per Sq. Inch
A
B
Mercury-Column of 1 Sq. In. Cross-Section, Weighs 14.696 Lb.

Fig. 11.—Equilibrium between column of atmospheric air and column of mercury of equal cross-section.

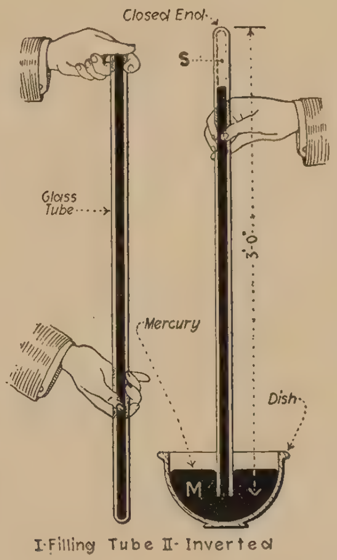


Fig. 12.—How a barometer may be made.

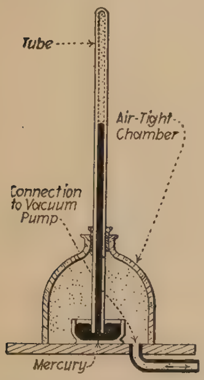


Fig. 13.—Height of mercury column decreases when air pressure is lowered.

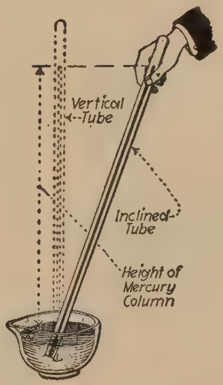


Fig. 14.—Mercury-column height remains the same for vertical or inclined tube.

space, S, above the falling column will be a practically perfect vacuum because there is no gas above the mercury. Hence the pressure on top of the mercury column will be practically zero.

But the pressure beneath the mercury column, at its base on the line AB (Fig. 11) will be the pressure of the atmosphere. If the experiment is made at sea-level, when the temperature of the air is 32° F., this pressure will (Fig. 11) be 14.696 lb. per sq. in. Therefore, the mercury-column will fall until, due to its height (weight), it will also exert a pressure of 14.696 lb. per sq. in. This condition of equilibrium will be attained when the mercury column falls to a height of 29.92 in. The nominal height of the barometer mercury-column at sea-level is usually taken as 30 in.

If the experiment is made at a point two miles above sea-level, the atmospheric pressure (Fig. 8), due to the 2-mile diminution in the depth of the atmosphere, will be about 9.6 lb. per sq. in. Equilibrium will then be established when the mercury-column falls to a height of 19.55 in.

If the mercury vessel of a barometer, constructed as above specified, be arranged in an airtight closed chamber with the mercury tube extending out of the top (Fig. 13) and the air be partially exhausted from the chamber, the mercury column will fall just as it would if the barometer were carried to a higher elevation. With a perfect vacuum in the chamber, the top of the mercury in the tube will be at the same level as that in the dish. When the dish is exposed to atmospheric pressure, however, the *vertical* height of the mercury column remains the same (Fig. 14) whether the tube is inclined or vertical.

11. The Aneroid Barometer (Fig. 15), since it is much more portable and less liable to derangement, is often used for measuring atmospheric pressures, instead of the mercurial barometer. This instrument may be so accurately constructed as to indicate a difference of elevation of 2 or 3 ft.

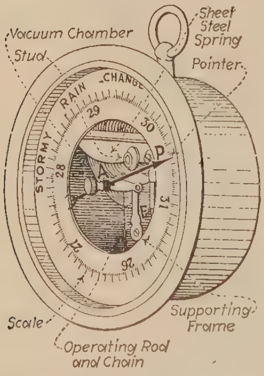


Fig. 15.—Aneroid barometer.

Explanation.—The corrugated top (Fig. 15) of the airtight cylindrical box, A, in which there is a partial vacuum, deflects slightly under changes in atmospheric pressure. This motion is transmitted, by a delicate lever system, F, to the pointer, P. The scale is graduated to read in equivalent inches of mercury column. In general, a *low barometer* indicates stormy weather, and a *high barometer* fair weather. Hence, barometer readings may be of assistance in predicting weather conditions.

12. Pressure Gages Are Instruments For Measuring Pressures (Figs. 16 and 22). Perhaps the simplest form of pressure gage is that shown in Fig. 16. This gage indicates the true (absolute, Sec. 15) pressure within the connected vessel. As is explained below, practically all commercial pressure gages indicate the pressure difference between the actual pressure which is being measured and the atmospheric pressure.

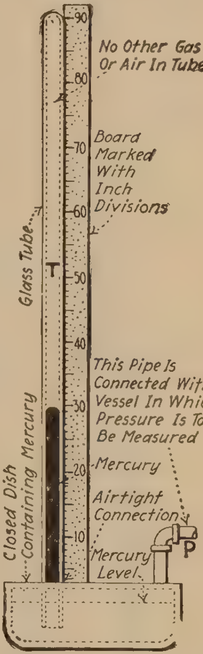

90
80
70
60
50
40
30
20
10
No Other Gas Or Air In Tube
Board Marked With Inch Divisions
Glass Tube
T
This Pipe Is Connected With Vessel In Which Pressure Is To Be Measured
Mercury
Airtight Connection
P
Mercury Level
Closed Dish Containing Mercury

Fig. 16.—A simple form of pressure gage. (As stated in the text, pressure gages similar to this one are not commonly used, because more practical gages can be made. See Div. 19 on instruments.)

Explanation.—The gage illustrated in Fig. 16 is constructed in exactly the same manner as is a mercurial barometer (Sec. 10). Hence, it measures the pressure in a connected vessel exactly as does a barometer measure atmospheric pressure. If the pipe, *P*, is left open to the atmosphere the gage will measure the atmospheric pressure. If *P* is connected to a vessel wherein the pressure is less than that of the atmosphere, the mercury will stand at a lesser height in tube *T* than it would when *P* is open to the atmosphere. Likewise, if *P* is connected to a vessel wherein the pressure is greater than atmospheric, the mercury will rise higher in *T*. Hence, *the height of the mercury column in T is a measure of the pressure in P.*

Unfortunately, the customary power-plant pressures could only be measured with such a gage as is shown in Fig. 16 by employing tubes, *T*, of lengths ranging from 20 to 60 ft. Hence, such gages are not commonly employed. Furthermore, for many purposes, the true pressure within a vessel is not as useful as is the pressure difference between the pressure in the vessel and that of the atmosphere. Therefore, gages, Fig. 18, which indicate how much above or below atmospheric pressure a given pressure is, are universally used. Note.—For a further treatment of pressure gages see Div. 19 on Instruments.

13. The Mercurial Manometer May Be Used For Indicating Pressures Above Atmospheric Pressure (Fig. 17). In the early days of steam-power, gages for indicating boiler pressure were made in this form. With such gages the difference, in inches, in height between the mercury levels in the legs of the

U-tube indicates, in inches of mercury column, the pressure above atmospheric pressure, in the vessel to which the instrument is connected. The operating principle of the mercurial manometer renders the instrument inconvenient, however, for indicating gage pressures higher than about 10 lb. per sq. in.; for higher pressures the tubes would have to be too long.

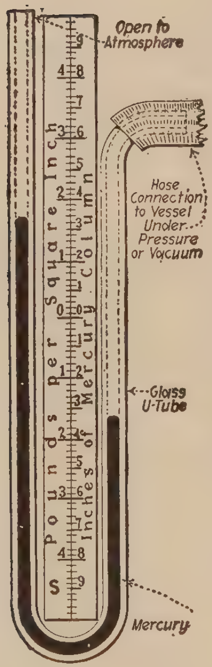


FIG. 17.—Mercury gage for measuring pressures above or below atmospheric. (The scale, *S*, shows that in *mercury column* readings are almost exactly 2 × *lb. per sq. in.* readings; actually 1 lb. per sq. in. = 2.036 in. mercury column.

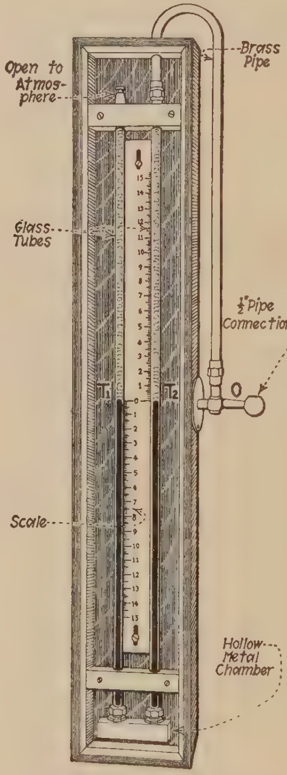


FIG. 18.—Mercurial power-plant vacuum gage. (Although this is called a vacuum gage, it can also be used for measuring small pressures greater than atmospheric. When the pressure in the chamber to which *O* connects is less than atmospheric, the mercury ascends in T_2 and descends in T_1 and vice versa.)

Note.—Mercurial Manometers Are Commonly Used In Power Plants For Indicating Degrees Of Vacuum (Sec. 16) which are produced in closed vessels. Instruments (Fig. 18) used for this purpose are frequently called *vacuum gages.* With such instruments the difference in the heights of the mercury columns, in legs T_1 and T_2, is an indication of the amount by which the external atmospheric pressure exceeds the absolute pressure within the vessel to which the instrument is attached.

Note.—Manometers For Measuring Very Small Pressure Differences Contain Water Instead Of Mercury.—Since mercury is (Fig. 19) 13.6 times as heavy as water, a column of water having an approximate height of 13.6 × 30 = 408 *in.* is required (Sec. 10) to balance the pressure of the atmosphere. Hence, very slight pressure differences, which might not visibly affect the height of a mercury column, would produce quite observable variations in the height of a water column.

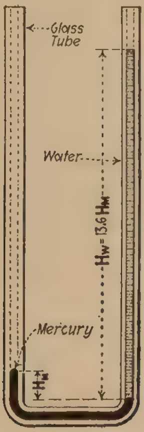


Fig. 19.—A column of mercury supports a column of water 13.6 times as high.

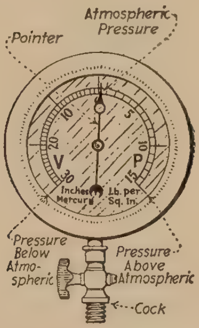


Fig. 20.—Combination pressure-and-vacuum gage.

14. Compound Pressure-and-vacuum Gages (Fig. 20) are employed in steam power plants. They operate on the same general principle as the Bourdon-tube steam gages which are discussed in Sec. 677. In the illustration the scale to the right, *P*, gives pressure readings. That to the left, *V*, gives vacuum readings.

15. The "Absolute" Pressure existing at any point in a fluid medium is understood to mean the true total pressure at that point—the term "absolute" being used to distinguish from "gage" pressure, which is defined in the following section. The absolute pressure may be (although it seldom is) measured with a gage like that of Fig. 16. The more customary method of determining absolute pressure is by measuring both the atmospheric pressure (with a barometer, Sec. 10) and the "gage" pressure. Since "gage pressure" indicates only the pressure above atmospheric pressure and since "absolute pressure" is *true total* pressure, it is evident that:

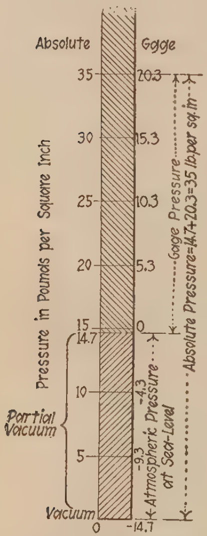

Absolute
Gage
35
30
25
20
15
14.7
10
5
0
20.3
15.3
10.3
5.3
0
-4.3
-9.3
-14.7
Pressure in Pounds per Square Inch
Partial Vacuum
Vacuum
Gage Pressure
Absolute Pressure=14.7+20.3=35 lb. per sq. in.
Atmospheric Pressure at Sea-Level

Fig. 21.—Relation between gage and absolute pressures.

(2) *Absolute pressure* = (*Atmospheric pressure*) + (*gage pressure*)

A negative gage pressure, when added, results in an absolute pressure which is less than the atmospheric pressure, as is explained in the following examples; see also Fig. 21.

Example.—If a boiler contains steam at 100 lb. per sq. in. gage pressure, as shown by the pressure gage on the boiler, and if the atmospheric pressure at that location and time is 14.5 lb. per sq. in., then the *absolute pressure within the boiler* = 100 + 14.5 = 114.5 *lb. per sq. in. absolute (abs.).*

Example.—If the vacuum gage attached to a condenser reads 26 in. of mercury column and the barometer (nearby) reads 29.5 in. of mercury column, the *absolute pressure within the condenser* = 29.5 − 26 = 3.5 *in. of mercury column absolute.*

16. The "Gage" Pressure existing at any point in a fluid medium is understood to mean the difference between the true (absolute, Sec. 15) pressure at that point and the pressure of the surrounding atmosphere. That is:

(3) *Gage pressure* = (*Absolute pressure*) − (*Atmospheric pressure*)

It is the pressure which is indicated by all commercial pressure gages, such as are shown in Figs. 17, 18, and 22. When such a gage is (Fig. 22) subject only to atmospheric pressure it shows no pressure or, as is sometimes said, "it reads *zero.*" Hence, "*zero gage pressure*" *means* "*atmospheric pressure*"—14.7 lb. per sq. in. at sea level. Whenever such a gage is connected to a vessel wherein the pressure exceeds atmospheric pressure (Fig. 23) the gage indicates a *positive gage pressure*, which is generally called simply a "gage pressure." If the gage is connected to a vessel wherein the pressure is less than atmospheric, it tends to indicate and will if designed therefor indicate a *negative gage pressure*, or simply a *vacuum*—"vacuum" being understood to mean "partial vacuum." Gages which are used for measuring negative gage pressures are commonly called *vacuum* gages. When compound pressure-and-vacuum gages (Sec. 14) indicate a vacuum, their pointers shift to the other side of the zero mark on the gage scale from the side of the mark on which pressures greater than atmospheric are indicated.

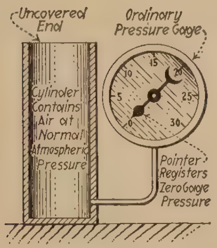

Uncovered End
Ordinary Pressure Gage
Cylinder Contains Air at Normal Atmospheric Pressure
0
5
10
15
20
25
30
Pointer Registers Zero Gage Pressure

Fig. 22.—Zero gage pressure coincides with normal atmospheric pressure.

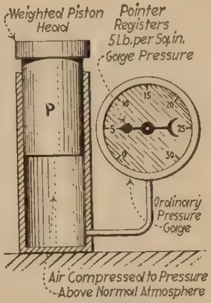

Weighted Piston Head
Pointer Registers 5 Lb. per Sq. in. Gage Pressure
P
0
5
10
15
20
25
30
Ordinary Pressure Gage
Air Compressed to Pressure Above Normal Atmosphere

Fig. 23.—Gage registers pressure above atmospheric pressure.

17. Approximate Absolute Pressures In Pounds Per Square Inch May Be Computed From Ordinary Gage-pressure Readings by the following formula. To obtain the exact absolute pressure, the exact atmospheric-pressure value, at the location under consideration, in pounds per square inch must be substituted for the "14.7" value which is shown in the formula.

$$P_A = P_G + 14.7 \qquad \text{(pounds per square inch)} \tag{4}$$

Wherein: P_A = absolute pressure, in pounds per square inch.

P_G = gage pressure, in pounds per square inch. 14.7 = average atmospheric pressure, at sea-level, in pounds per square inch.

Example.—A steam gage connected to a boiler reads 150 lb. per sq. in. What is the approximate absolute pressure within the boiler? Solution. Substitute in For. (4): $P_A = P_G + 14.7 = 150 + 14.7 = 164.7$ *lb. per sq. in. = absolute pressure within the boiler.* However, the stresses in the boiler shell are only those due to a pressure of 150 lb. per sq. in. This is because the surrounding atmosphere presses from the outside against the shell in all directions with a pressure of 14.7 lb. per sq. in.

18. To Reduce Water- And Mercury-column Pressures To Pounds Per Square Inch and Vice Versa, the following equations may be used:

(5) $$P = \frac{P_M}{29.92} \times 14.696 = 0.491{,}2P_M$$ (pounds per square inch)

(6) $$P_M = \frac{P}{0.491{,}2} = 2.036P$$ (inches of mercury column)

(7) $P_M = 0.073{,}55P_I$ (inches of mercury column)

(8) $P_I = 13.596P_M$ (inches of water column)

(9) $P_I = 27.684P$ (inches of water column)

(10) $P_F = 2.307P$ (feet of water column)

(11) $P = 0.036{,}13P_I$ (pounds per square inch)

(12) $P = 0.433{,}5P_F$ (pounds per square inch)

Wherein: P = the pressure, in pounds per square inch. P_M = the height of the mercury column, at atmospheric temperature, in inches. P_I = the height of water column, at atmospheric temperature, in inches. P_F = the height of water column, at atmospheric temperature, in feet.

Note.—The Customary Units For Measuring Pressures Are: (1) *Atmospheric pressure and partial vacuums* are generally measured in inches of mercury column. (2) *Gas pressures*, when small, are measured in inches of water column. (3) *Hydraulic pressures* are frequently measured in feet of water column. (4) *Pounds per square inch* is the general engineering unit and is used in nearly all work except that specified above and frequently also for some of the purposes given in (1) to (3).

19. Table Showing Relation Among Units Of Pressure.—The liquid columns are assumed to be measured at normal atmospheric temperature.

Name of unit	Pounds per square inch, P	Pounds per square foot	Inches of mercury column P_M	Inches of water column P_I	Feet of water column P_F
Pound per square inch..............	1	144	2.037	27.684	2.307
Pound per square foot..............	0.006,94	1	0.014,1	0.192,2	0.016
Inch of mercury column.............	0.491,2	70.733	1	13.596	1.136
Inch of water column...............	0.036,13	5.203	0.073,55	1	0.083,3
Foot of water column...............	0.433,5	62.424	0.881,9	12	1

EXAMPLES.—*A pressure of* 1 *lb. per sq. in.* = *a pressure of* 144 *lb. per sq. ft. A pressure of* 1 *in. mercury column* = 0.419,2 *lb. per sq. in.*

20. "Work" Is The Overcoming Of Opposition Through Space.—(Note that "work," as the word is used in engineering has a meaning different from its meaning in ordinary conversation.) Work is done when force is overcome through distance. Whenever anything is moved, then work is done. When there is no movement, there is no work. To compute the work done in overcoming force through distance, two factors must be known: (1) *The applied force.* (2) *The distance.* The distance must be measured in the same direction as that of the force.

21. Numercial Expressions Of Work may be obtained by multiplying the applied force by the distance through which the force moves. The force may, in practice, be expressed in any unit of force. The distance may be expressed in any unit of length. The *unit of work* is then formed by multiplying together the given units of force and distance. Hence, the formula:

$$W = FL \qquad \text{(work)} \tag{13}$$

Wherein: W = the work, expressed in the assumed unit-terms of the force and distance. F = the force, expressed in any assumed unit of force. L = the distance, expressed in any assumed unit of length.

NOTE.—If, in For. (13), F = pounds and L = inches, then W = inch-pounds If F = pounds and L = feet, then W = foot-pounds. If F =

tons and L = miles, then W = mile-tons. If F = grams and L = centimeters, then W = gram-centimeters. And so with other combinations of the units of force and length.

22. The Unit Of Work Which Is Used Most Frequently in the United States is the *foot-pound.* A *foot-pound* is the work done when a 1-lb. force is overcome through a distance of 1 ft.

NOTE.—THE METRIC UNITS OF WORK MOST FREQUENTLY USED are, (Table 4) the *gram-centimeter* and *kilogram-meter.* These units are largely employed in South America and in Continental Europe. They are now little used in America.

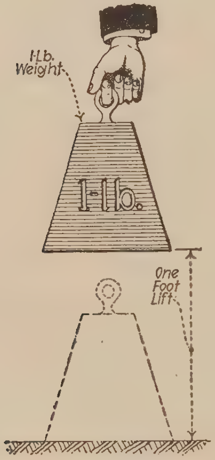


FIG. 24.—One foot-pound of work done against gravity.

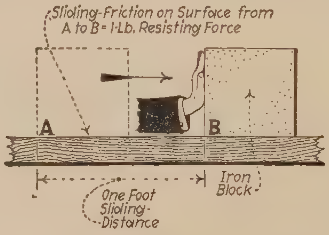

Sliding-Friction on Surface from A to B = 1-Lb. Resisting Force
A
B
Iron Block
One Foot Sliding-Distance

FIG. 25.—One foot-pound of work done against friction.

EXAMPLE.—A 1-lb. weight (Fig. 24) is lifted vertically to a height of 1 ft. Here the opposing force (Sec. 2) is a gravity-pull of 1 lb. The distance through which the opposition is overcome is 1 ft. Hence, by For. (13) the work done = $W = FL = 1 \times 1 = 1$ *ft.-lb.* = 1 *unit of work.*

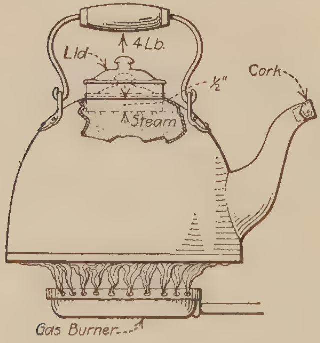


FIG. 26.—Steam in kettle raising lid and thereby doing work.

FIG. 27.—Doing work in lifting a shovel of coal.

Example.—A block of iron (Fig. 25) is pushed through a horizontal distance of 1 ft., along a wood surface. The friction between the iron and the wood develops an opposing force of 1 lb. Hence, by For. (13), the work done = $W = FL = 1 \times 1 = 1$ *ft.-lb.* = 1 *unit of work.*

Example.—The lid of a kettle (Fig. 26) fits tightly. A total force of 4 lb. is required to lift it. The steam, which is generated in the kettle, pushes the lid upward 0.5 in. What quantity of work is done? Solution.—By For. (13), $W = FL = 4 \times 0.5 = 2$ *in.-lb.*

Example.—A man (Fig. 27) lifts a 25-lb. shovel of coal 2 ft. from the floor. Hence, by For. (13), the work which he does = $W = FL = 25 \times 2 = 50$ *ft.-lb.*

Example.—A compressed-air hoisting cylinder (Fig. 28) lifts a 125 lb. weight 16 in. Hence, by For. (13), the work done = $W = FL = 125 \times 16 = 2{,}000$ *in.-lb.* = 2,000 ÷ 12 = 166.5 *ft.-lb.*

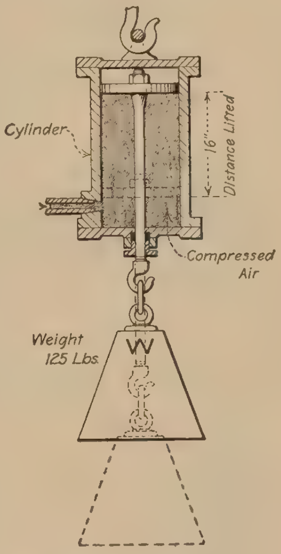


Fig. 28.—Work being done by an air hoist.

23. "Energy" Is Capacity For Doing Work; this is the technical meaning of the word. Energy is ability to do work. It is stored work. Any body or medium which is of itself, due to its position or state, capable of doing work, is said to possess *energy*. Work must, then, have been previously done on the body to change its state or to give it the position whereby it possesses the capacity for doing work. It is impossible to create energy, nor can energy be destroyed. Hence, the amount of energy in the universe is always constant.

Note.—Energy Is An Attribute Of All Matter.—It is inherent in matter. (Matter is anything which has weight or which occupies space.) This follows (Sec. 3) from the fact that position in space is a property of all matter. Therefore, since matter is (Sec. 39) universal, energy must likewise be universal. Just as there is a definite amount of matter in the universe, so is there a definite amount of energy in the universe. And just as the matter may exist in various aspects, so likewise may the energy exist in various aspects.

24. "Energy" May Be Expressed In The Same Units As Are Used To Express Quantities Of Work (Sec. 22).—This follows from the fact that energy is merely stored work, or

(Sec. 23) capacity for doing work. Thus the *foot-pound* is the commonly-used unit of energy as well as it is of work.

Example.—Energy or work is stored in the ball of Fig. 29. Work was expended in lifting the ball 15 ft. Since the ball weighs 1½ lb., the work done in lifting it from the table top to the position shown is, by For. (13): $W = FL = 1.5 \times 15 = 22.5$ *ft.-lb.* The ball then, with respect to its original position on the table, possesses 22.5 ft.-lb. of energy. Now, if this elevated ball were attached to some machine, such as a clock, and permitted to descend to the table top, 22.5 ft.-lb. of work (neglecting friction) would be given up by and could be realized from it.

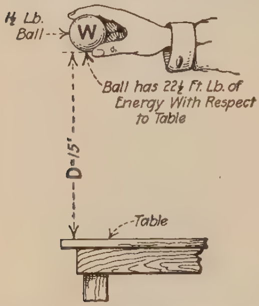


Fig. 29.—Ball possesses energy due to its position. (Drawing not to scale.)

25. There Are Two Fundamental Forms Of Energy, "Kinetic" And "Potential."—These forms are, sometimes called respectively *energy of motion* and *fixed energy.* Kinetic energy may be transformed into potential energy and vice versa. Bodies possess potential energy by virtue of their positions or conditions. Bodies possess kinetic energy by virtue of their motion.

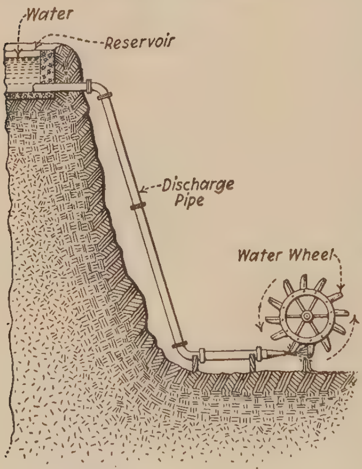


Fig. 30.—Energy of water from reservoir driving water wheel.

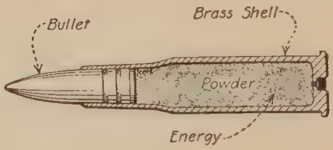


Fig. 31.—Powder in the rifle cartridge possesses potential chemical energy.

Examples.—Since the now stationary ball, *W*, shown in Fig. 29 may do work, if permitted to descend, it possesses potential energy, due to its position. The main spring of a clock may possess potential energy, due to its condition of being wound. Water in a reservoir (Fig. 30) has energy, due to its position. Powder (Fig. 31) has potential energy, due to its explosive properties. A bullet projected from a gun has kinetic energy, due to its motion, and is, thereby, able to pierce (Fig. 32) an iron plate. In so doing, part of its kinetic energy is converted into the work of piercing the plate. A falling hammer (Fig. 33) has kinetic energy.

Note.—Energy May Be Further Divided Into *mechanical, chemical, electric, radiant,* and *heat* energy. Each of these forms will be discussed in following sections. As explained in the following section, any one kind of energy may, by employing suitable machines or processes, be transformed into any other kind of energy.

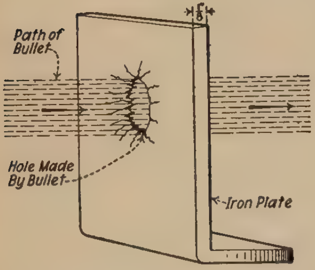


Fig. 32.—Energy of rapidly moving bullet enables it to pierce iron plate.

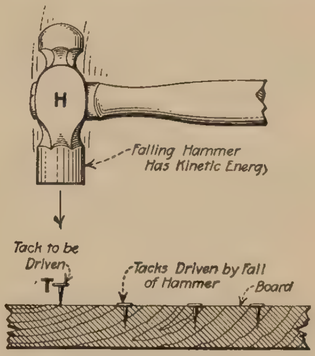

H
Falling Hammer Has Kinetic Energy
Tack to be Driven
T
Tacks Driven by Fall of Hammer
Board

Fig. 33.—Kinetic energy of falling hammer drives tacks.

26. Energy May Be Transformed From One Kind To Another.—Whenever there is motion there is energy transformation; all mechanical processes offer examples of it. Our everyday life is simply a succession of such energy transformations. Sometimes a process may be traced through an entire long series of energy transformations.

Examples.—A man eats a meal; a portion of the meal goes toward building up his muscular tissues thus storing chemical energy therein; he picks up a ball from the ground thus imparting potential energy to the ball; he throws the ball into the air thus imparting kinetic energy to the ball. The energy which was imparted to the ball was derived from his muscles. The kinetic energy of the ball, after he releases it, gradually becomes transformed into potential energy as the ball rises. Soon the ball ceases to rise. It begins to fall—it again acquires kinetic energy, this time at the expense of its potential energy. Having struck the ground, the ball has lost all of its potential energy (we may say, see also Sec. 85) but it now possesses much kinetic energy. It may deform the earth where it strikes and thus heat the ground and itself. Eventually, probably, all of the chemical energy which the man expended in lifting and throwing the ball will be transformed into heat energy. But this heat energy is given to the earth or our atmosphere where it remains until it has a chance to do further work. It may stimulate plant life and thus help to produce more of that substance from which the man derived his chemical energy—that is, his food. Thus, the transformation of energy will, perhaps, go on forever. See also Table 33.

Note.—The State In Which Matter Exists May Change.—So also, the state in which energy exists may change. What is now liquid iron, of a pale orange color in the pouring-ladle, changes to plastic iron, of a cherry-red color in the mold, and again to hard grey iron in the finished casting. So, likewise, what is now chemical energy in a coal pile may be changed to mechanical energy by a steam engine, thence to electrical energy by a dynamo, and, perhaps, to active heat and radiant (light) energy in an electric lamp.

27. Mechanical Energy is that form of energy which may be realized directly as mechanical work. A watch spring, when wound, is capable of doing mechanical work in unwinding; it possesses potential mechanical energy. A rotating flywheel has energy of motion; it does the work of carrying the moving parts of an engine onward at the instants when the connecting rod is passing the dead centers. It has kinetic mechanical energy. See Table 33.

28. Chemical Energy (sometimes called "Internal" energy) is the energy which is normally "bound up" *within the molecules* of all substances. When a chemical process or reaction—a rearrangement and transfer of the constituent atoms of the molecules (Sec. 155)—occurs, some of the internal chemical energy may thereby be automatically released from the molecules of the substances which participated in the reaction. Then this chemical energy will be automatically transformed into heat energy, electrical energy, or mechanical energy—as determined by the reaction and the conditions under which the reaction occurred. Conversely, to effect certain other chemical processes it is necessary to add energy—heat energy, electrical energy or mechanical energy—to the substances involved to cause the transfer and rearrangement of the atoms of the molecules necessary to produce the new desired substances. When energy is thus added to substances to effect a chemical reaction, it then becomes "bound up" or latent as chemical energy within the molecules of the new resulting substances—and will remain so—unless part or all of it is later released, and transformed into some other kind of energy, by some subsequent chemical process. These phenomena are further discussed in Sec. 157. See also Sec. 437 and Sec. 461.

EXAMPLES.—The burning of any fuel is a chemical process, combustion (see Div. 14). Combustion is a chemical union of oxygen with the fuel substance; the usual products are heat energy, a gas called carbon dioxide, other gases, and water. When combustion occurs part of the chemical energy which was stored in the fuel and in the oxygen is liberated as heat energy.

By the mechanical rubbing of silver chloride, a solid, it can be decomposed into silver, a metal, and chlorine, a gas. Heat energy from the friction of the rubbing, is absorbed, partly by the silver and partly by the chlorine, during this chemical process. The absorbed heat energy then resides latent in the chlorine and the silver. Mechanical energy has been transformed into chemical energy.

Powder (Fig. 31) possesses a large amount of chemical energy which may be liberated and utilized ultimately as mechanical energy to force a bullet out of a shell and through a rifle barrel; when the powder burns, it is converted into a gas at a very high temperature and pressure; the pressure imparts motion to the bullet. When an electric spark is formed in a suitable gas mixture in a gas engine (Fig. 34), an explosion results. This is a manifestation of chemical energy being transformed into mechanical energy. The high pressure, thus developed above the piston, results, finally, in the rotation of the crankshaft. When a zinc bar and copper bar (Fig. 35) are immersed in certain acid solutions, a chemical action results which forces an electric current to flow—an example of the transformation of chemical energy into electrical energy (see also Table 33).

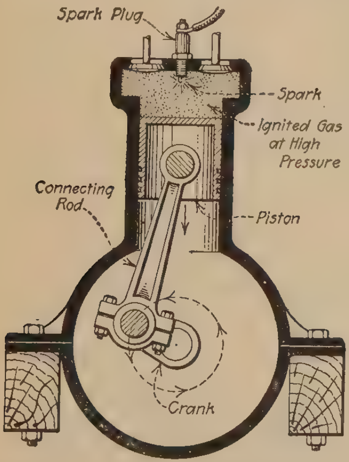


FIG. 34.—Energy developed by gas engine as a result of chemical reaction.

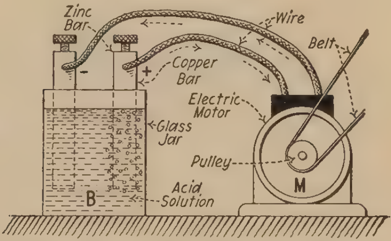


FIG. 35.—Electric current circulated due to chemical energy.

29. No Change In Chemical Composition—That Is, No Chemical Reaction—Can Occur Without The Liberation Or Absorption Of Energy.—The energy may be either heat, radiant, electrical, or mechanical energy, or some combination of them, depending on the reaction and the conditions under which it occurred. The preceding sums the results of many experiments. In this book it is, principally, the liberation and absorption of heat energy which are of interest, which is further treated in Sec. 156.

30. Electrical Energy is, in the kinetic form, the energy possessed by a current of electricity. Or, in the potential form, it is the energy possessed by a "charge" of electricity, stored in a condenser. Since an electric current is a flow of electricity—electricity in motion—such a current has kinetic energy. The energy of an electrical charge stored in a condenser is potential. This follows, since such a charge is, for the time being, fixed or stored.

Note.—An electric generator (Fig. 36) is a machine which transforms mechanical energy into electrical energy. Mechanical energy may be imparted to the generator by an engine, turbine, or waterwheel. The generator, thus driven mechanically, forces an electric current (a stream of electrons, Sec. 42) to flow in the circuit. Thereby electrical energy is developed. Electrical energy may be reconverted into mechanical energy (Fig. 36) by electric motors. Electromagnets and electric heaters convert electrical energy into magnetic energy and heat energy, respectively.

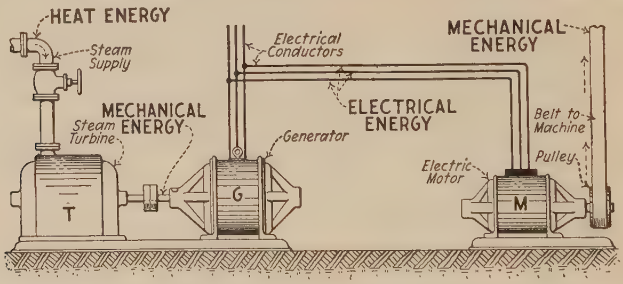


Fig. 36.—Illustrating conversion of energy—electrical energy transmitted from generator to motor.

31. Radiant Energy is the name which is given to that form of energy propagation from a hot body, by waves in the æther, which produces the sensations of "light" and "heat" when the waves strike objects. Hence, radiant energy is classified as a form of kinetic energy. The action of light causes certain chemical changes. For example, light acting on a photographic plate (Fig. 37) induces chemical changes which render photographs possible. Light acting upon plants causes them to grow and assume characteristic colors. See Div. 5 "Transfer Of Heat" for further discussion of radiant energy.

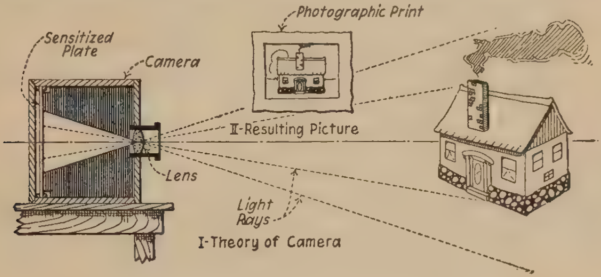


Fig. 37.—Light energy affects photographic plate.

Note.—The Earth's Principal Source Of Radiant Energy Is The Sun (Sec. 65).

32. Heat Energy Or Heat (Fig. 38) is, as explained in Div. 2., believed to be a condition of motion. The molecules of all substances are (except theoretically at absolute zero. Sec. 61), vibrating constantly and separated from one another. This vibration and separation produce the phenomena of heat,

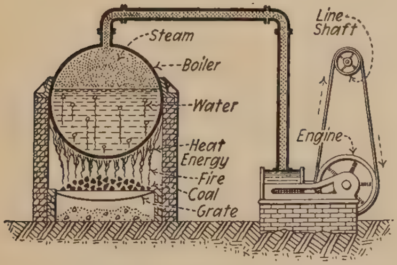


Fig. 38.—Heat energy from fuel converted into mechanical energy by engine.

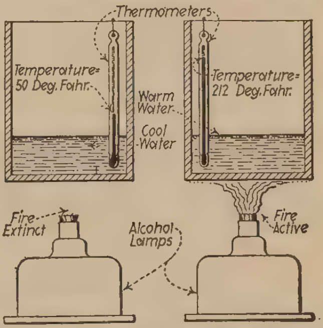


Fig. 39.—Heat energy raises the temperature of a body.

The speed of vibration of the molecules of a substance determines its temperature (Sec. 55). Hence, the vibration of the molecules is kinetic heat energy. The separation of the molecules is a state of potential heat energy. These ideas are explained at greater length in Div. 4. See examples of heat-energy transformations in Table 33.

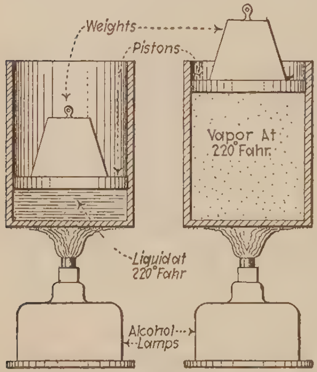


Fig. 40.—Heat energy changes a liquid to a vapor and thereby does mechanical work.

Note.—Various Phenomena Result From Applications Of Heat Energy.—The temperatures (Fig. 39) of substances are raised thereby. By the addition of heat, substances are changed from a solid to a liquid condition, or (Fig. 40) from a liquid to a gaseous or vaporous condition. When heated, bodies are caused (Sec. 159) to expand or increase in volume. These phenomena are discussed in detail hereinafter.

33. Table Of Examples Of Energy Transformations.—The examples here given are not to be understood as being the only instances of the transformations which they illustrate. (From The Thermodynamics of Heat-engines by Reeve.)

Transformation		Example
From	To	
Mechanical	Heat	The heating of a body subjected to friction or impact.
	Electrical	The electric generator or the glass-plate electric machine.
	Chemical	The setting-off of a detonating compound, such as fulminate of mercury or nitroglycerine.
Electrical	Heat	The heating of any conductor by the passage of an electric current; the electric heater.
	Chemical	The electrolysis of a chemical compound by the passage of a current, as in electroplating or in the charging of a storage battery.

Transformation		Example
From	To	
Electrical.........	Mechanical	The electric motor; the solenoid.
Chemical..........	Heat	The combustion of fuels; animal heat.
	Electrical	The evolution of an electric current from a battery.
	Mechanical	Animal activity; the evolution of a gas from the combination of two solids or liquids as in the chemical fire engine.
Heat.............	Electrical	The thermopile or thermocouple (pyrometer).
	Chemical	The lime-kiln; the growth of vegetation.
	Mechanical	The expansion of a heated body; the steam engine.

NOTE.—THERMODYNAMICS is that branch of physical science which treats of the relation between heat and mechanical work. Hence, the portions of this book which consider the relation between these two forms of energy constitute, in reality, a treatment of elementary thermodynamics.

34. The Distinction Between Energy And Work dwells in the simple concept that work is a manifestation of energy. Work and energy—since they are both measured in the same unit, the foot-pound for example—are sometimes confused one with the other. Energy (Sec. 23) is a common property of all matter (note subjoined to Sec. 23). In fact, there is a recent theory, which is gaining recognition, that all matter is simply motion. If the theory is accepted, then all matter would be energy. Work (Sec. 20) is the medium through which the energy which resides in any portion of matter reveals its presence. When a quantity of energy is dormant, that is, when it is potential energy (Sec. 25), then work, so far as that particular quantity of energy is concerned, is in abeyance. The dormant energy may then be said (Sec. 23) to impart capacity for doing work to the body of matter within which it resides. When the same quantity of energy is active, that is, when it is permitted to overcome opposition through a distance, that energy is revealed as work. The active energy may then be said to have developed or vitalized its dormant capacity for doing work.

35. "Power," in its technical sense, is the *rate of doing work*. In *work* and *energy* only two factors, i.e., *force* and *distance*, are the elements. In *power* there is a third factor, i.e., *time*. Observation proves that a machine which does a certain amount of work in 1 min. must be larger—more powerful—than another which does the same work in 2 min. A small machine may ultimately do the same amount of work as a larger one, but the small one requires more time to do it. The power of a machine is, then, determined by calculating the work which it does per unit of time. Hence the formula:

$$\mathbf{P} = \frac{W}{t} \qquad \text{(power)} \tag{14}$$

Wherein: **P** = the average power expenditure, during the time interval t, expressed as a number of work units of the given denomination, per the selected unit of time. W = the work done during the time interval t, expressed in any desired unit of work. t = the time, expressed in any desired unit of time, in which the given quantity of work, W, is done.

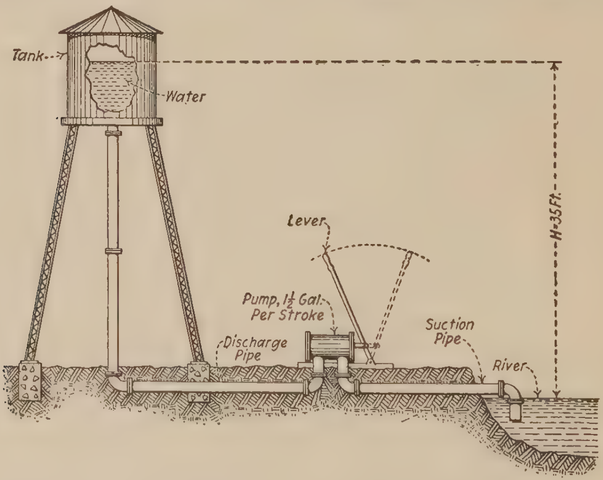


Fig. 41.—Example of power required to pump water.

Note.—If, in For. (14), W = foot-pounds and t = minutes, then **P** = foot-pounds per minute. If W = inch-pounds and t = seconds, then **P** = inch-pounds per second. If W = mile-tons and t = days, then **P** = mile-tons per day. And so with other combinations of the units of work and time.

EXAMPLE.—To get water into a tank (Fig. 41) the water must be lifted 35 ft. The pump-lever makes 20 strokes per min. The quantity of water pumped at each stroke is 12 lb. What is the rate of doing work, that is, what power is being expended while the water is being pumped? SOLUTION.—By For. (13), the work done at each stroke = $W = FL = 12 \times 35 = 420$ *ft.-lb.* The time consumed in doing this quantity of work = $1 \div 20 = 0.05$ *min.* Hence, by For. (14), the *power developed* = $\mathbf{P} = W/t = 420 \div 0.05 = 8{,}400$ *ft.-lb. per min.*

36. The "Horsepower" Is A Unit Of Power.—Any unit of power is an expression for a certain amount of work (Sec. 20) done in one unit of time. The unit of power which is commonly used in engineering is the horsepower. By definition, *the horsepower expresses the doing of work at the rate of 33,000 ft.-lb. per min.* That is, when work is done at the rate of 33,000 ft.-lb. per min., the power being expended is then 1 hp. Note that 1 hp. = 550 *ft.-lb. per second* = 33,000 *ft.-lb. per minute* = 1,980,000 *ft.-lb. per hour.*

NOTE.—THE HORSEPOWER UNIT WAS FORMULATED BY JAMES WATT as a basis from which to compute the capacities of engines for mine service. From empirical data which he had obtained, Watt calculated that a heavy draft horse, of the breed which had previously been generally used for hoisting coal out of mines, could do work regularly at the rate assumed, viz., at the rate of 33,000 ft.-lb. per min. It was later determined, however, that this assumed unit is much above the average daily working capacity of horses.

NOTE.—THE UNIT OF POWER WHICH IS GENERALLY USED IN THE METRIC SYSTEM is the kilogram-meter per second. One meter = 39.37 in.

37. The Average Power, In Horsepower Units, Which Is Developed By Any Apparatus Or Agency For Doing Work may be computed by the following formula:

$$\mathbf{P} = \frac{FL}{33{,}000t} \quad \text{(horsepower)} \tag{15}$$

Wherein: **P** = the average power, or rate of doing work, in horsepower, during the time interval, t, in which the work is done. F = the applied force, in pounds. L = the distance through which the force acts, in feet. t = the time, in minutes, during which the force is applied.

Note.—The nominal rate at which a steam engine or other apparatus does work is conventionally spoken of as *its horsepower rating*.

Example.—The number of pushes and pulls, per minute, of an engine piston (Fig. 42) is 60. The average total force on the piston is 6,000 lb. The length of the stroke is 10 in. What horsepower is being developed while the engine is in operation? Solution.—The *distance traversed by the force, per minute* = 60 × 10 ÷ 12 = 50 *ft.* Hence, by For. (15), $P = FL/33{,}000t = (6{,}000 \times 50) \div (33{,}000 \times 1) = 9.09$ *hp.*

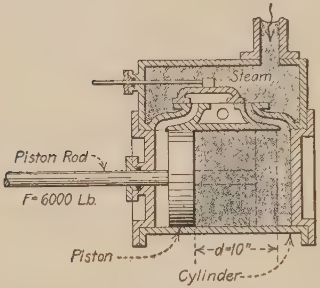


Fig. 42.—Example of power development by a steam engine cylinder.

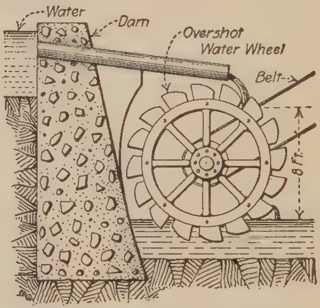


Fig. 43.—Power developed by an overshot water wheel.

Example.—The effective weight of water flowing from the trough of an overshot wheel (Fig. 43) is 4,000 lb. per sec. The vertical distance, through which the water falls, is 8 ft. What horsepower is being developed? Solution.—The *given time* = 1 *sec.* = $\frac{1}{60}$ *min.* Hence, by For. (15), $P = FL/33{,}000t = (4{,}000 \times 8) \div (33{,}000 \times \frac{1}{60}) = 58.18$ *hp.*

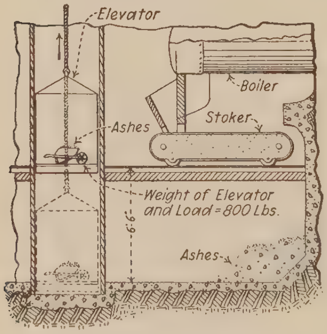


Fig. 44.—What power is required to raise the ash-lifting elevator?

Example.—A loaded elevator (Fig. 44) weighs 800 lb. A motor lifts it 6 ft.-6 in. in 30 sec. What horsepower is the motor developing? Solution.—The given *distance* = 6 *ft.* 6 *in.* = 6.5 *ft.* The given *time* = 30 *sec.* = $\frac{30}{60}$ = 0.5 *min.* Hence, by For. (15), $P = FL/33{,}000 = (800 \times 6.5) \div (33{,}000 \times 0.5) = 0.315$ *hp.*

Example.—A motor is belted to a machine. The belt travels 450 ft. per min. The difference, in tension, between the two sides of the belt is 50 lb. What horsepower is being transmitted? Solution.—By For. (15) $= FL/33{,}000t = (50 \times 450) \div (33{,}000 \times 1) = 0.68$ *hp.*

QUESTIONS ON DIVISION 1

1. What is *force?* What effect does it have upon a moving body? Give examples.

2. What are the common units of force? Give examples.

3. What is *pressure?* What kind of substances are generally spoken of as exerting pressure?

4. How does the fluid pressure at a point vary with the direction in which it is measured?

5. State two general classes of pressure units and give examples of each.

6. What is *atmospheric pressure?* How is it measured? Give a general description of the mercurial barometer.

7. Why is a man standing on the ground under a heavier atmospheric pressure than a man flying in an airplane?

8. What are pressure gages? Explain two ways in which pressures may be measured.

9. What is *gage pressure? Absolute pressure?* State how each is measured.

10. Define *work.* What factors are needed in calculating the amount of work done? Explain with an example.

11. What is the unit of work? State examples of its application.

12. Give and explain the formula for computing work.

13. What is energy? Can it be destroyed?

14. What is the unit of energy? Give an example of its application.

15. What is meant by *kinetic energy?* Give example. *Potential energy?* Give example.

16. Give practical examples of *mechanical energy* and tell whether they are kinetic or potential.

17. What is meant by *chemical energy?* Give example.

18. Give an example of kinetic energy in electrical form. Likewise potential energy.

19. Why is light classified as a form of energy?

20. Discuss heat with reference to energy. Is heat energy?

21. What is *power?* How is the power of a machine determined? Give an example.

22. What is the principal unit of power? Give an example of its application.

23. Give and explain the formula used in power calculations.

PROBLEMS ON DIVISION 1

1. What force, in pounds, is required to lift, vertically, a cart of coal which has a total weight of 1 (short) ton?

2. Is a wrench, which is lying on the floor and which weighs 5 lb., subjected to any force? What effect is due to the weight of the wrench?

3. An engine with its concrete foundation weighs 20,000 lb. Its base area is 50 sq. ft. What pressure, in terms of the weight and area as here given, does the foundation impose on the supporting soil?

4. A steam gage registers 128 lb. per sq. in. What is the absolute pressure? (Assume standard atmospheric pressure.)

5. What pressure, in pounds per square inch, is indicated by a barometer reading of 28.5 in. of mercury column?

6. What height of mercury column will balance a 30-ft. water column?

7. If the man in Fig. 2 pulls 12 lb. with his left hand, what will he be pulling with his right? Why?

8. If a car loaded with coal, weighs 100,000 lb. and the resistance to rolling totals 5 per cent. of its weight, how much draw-bar pull will be required to keep the car moving slowly?

9. If a bucket of coal weighs 50 lb., how much work will be required to carry it up a set of steps to a point which is 15 ft. higher?

10. A punch exerts an average push of 35,000 lb. in punching a hole in a piece of armor plate ½ in. thick. How much energy is required to punch the plate? (Assume that the 35,000 lb. is exerted through the ½-in. distance.)

11. The tension of one side of a belt is 65 lb., and on the other 140 lb. The belt is traveling 300 ft. per min. What is the horsepower transmitted?

12. What is the horsepower of the head end of a steam cylinder, when the average pressure on the piston rod is 3,500 lb., the stroke 15 in., and the revolutions per minute of the flywheel, 90?

13. A pump will deliver 1,500 gal. of water per minute to a water level, 350 ft. above the pump. If water weighs 8.3 lb. per gal., at what rate is the pump doing work, in foot-pounds per minute and in horsepower?

14. A 6-hp. motor is used to pump water from a well 75 ft. deep. If the motor is running at full capacity, and all losses neglected, compute the number of gallons of water raised in three hours. (Water weighs 8.3 lb. per gal.)

DIVISION 2

MATTER, HEAT, TEMPERATURE

38. A Knowledge Of Certain Fundamental Concepts Regarding The Material World Is Necessary To An Understanding Of The Phenomena Of Heat.—If the various substances or materials which we recognize about us, such as *air, iron, wood, water* did not exist, there could be no heat, for heat is a condition of materials. The heat sensations which we experience, as emanating from substances, are manifestations of this condition.

39. "Matter" Is That Of Which Every Substance In The Material World Is Formed; this is the technical definition of matter. But all matter is not of one kind. Different kinds of matter (Fig. 45) form different substances. Thus there are thousands of different kinds of matter.

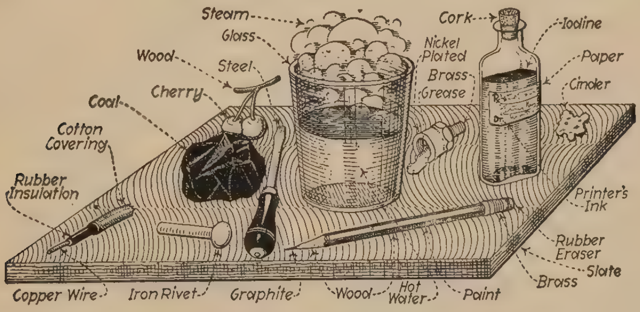


FIG. 45.—Different substances all made up of matter.

NOTE.—A SUBSTANCE IS ANYTHING WHICH HAS WEIGHT AND VOLUME.—Therefore, anything that has weight, and which occupies space, is *matter*. Consequently, anything that can be recognized by sight, touch, taste or smell is *matter*. But not all substances are evident to the four senses here enumerated. Many substances, as *air* and *oxygen*, are quite unapparent to these senses. Yet such substances have weight and occupy space, and hence are *matter*.

Note.—Universal Space Which Is Not Occupied By Matter Is Occupied By Æther (Sec. 46). Hence, the universe comprises only two fundamental components: (1) *Matter.* (2) *Æther.*

40. Matter Is Composed Of Minute Particles Called Molecules.—These particles are so small that one of them, if it were possible to separate it from all others, would be invisible even under the most powerful microscope. It is not anticipated that magnifying instruments strong enough to render molecules observable to the human eye will ever be perfected.

Note.—The Molecules Of Different Substances, as *wood, glass, steel, rubber, air, oil,* are differently constituted. There are as many kinds of molecules as there are substances or kinds of matter.

41. Molecules Are Composed Of Smaller Particles Called Atoms (Fig. 46). Atoms are, probably, as much smaller than some molecules as molecules are smaller than the smallest particle of matter which may be discerned through the strongest microscope yet produced. Only a few more than about 80 different kinds of atoms have thus far been isolated (from atoms of different kinds—a single atom has not been isolated) and identified. It is said that no more than 92 different kinds are possible. All matter is, therefore, built up of molecules in which one or more of these 92 different kinds of atoms subsist in various combinations and arrangements.

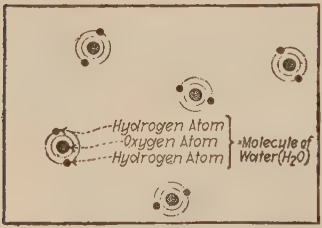


Fig. 46.—An imaginary picture of the molecules of water each of which is composed of three atoms—one of oxygen and two of hydrogen. The 3 atoms remain in a group. The molecules move about—often colliding.

Note.—A Substance The Molecules Of Which Are Composed Of But One Kind Of Atom Is Called An Element (Table 42). The molecules of most substances, as *soap, rubber, steel, brick, flesh, albumen,* are composed of more than one kind of atom. The molecules of a substance may contain hundreds of atoms, even though many be of one kind. The molecular composition of every substance, as regards the kinds of atoms and the numerical combinations thereof, is invariable for that substance. Generally, when the molecular composition of a substance is changed the nature of the substance likewise is changed.

42. Table Giving The Most Common Chemical Elements, With Symbols.

Element	Symbol	Element	Symbol	Element	Symbol
Aluminum	Al	Fluorine	F	Nitrogen	N
Antimony	Sb	Glucinum	Gl	Oxygen	O
Argon	A	Gold	Au	Phosphorus	P
Arsenic	As	Helium	He	Platinum	Pt
Barium	Ba	Hydrogen	H	Potassium	K
Bismuth	Bi	Iodine	I	Silicon	Si
Bromine	Br	Iron	Fe	Silver	Ag
Calcium	Ca	Lead	Pb	Sodium	Na
Carbon	C	Lithium	Li	Sulphur	S
Chlorine	Cl	Magnesium	Mg	Tin	Sn
Chromium	Cr	Manganese	Mn	Tungsten	W
Cobalt	Co	Mercury	Hg	Zinc	Zn
Copper	Cu	Nickel	Ni		

Note.—Every Atom Is Believed To Be Composed of Smaller Particles Called Electrons Together With A Positive Nucleus.—

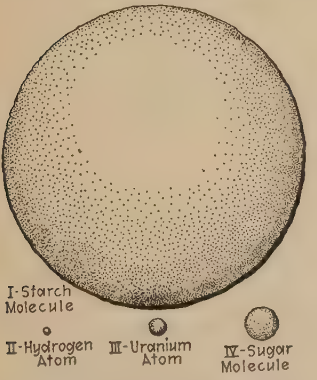


Fig. 47.—Comparison of sizes of smallest and largest atoms and molecules (Comstock & Trowland).

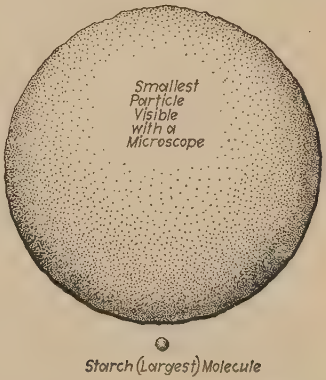

Smallest Particle Visible with a Microscope
Starch (Largest) Molecule

Fig. 48.—Comparative sizes of largest molecule and smallest microscopically visible particle (Comstock & Trowland).

An electron is a natural particle of negative electricity. The electrons which compose an atom are presumed to rotate in regular orbits about a center or *nucleus* of positive electricity of the atom, in much the same way as the four moons rotate around the planet Saturn. Hence it appears that, in its ultimate composition, all matter is, probably, composed of electricity. In the discussion which follows, the atom will be regarded as the ultimate division of matter. The electron theory is explained in the author's PRACTICAL ELECTRICITY.

NOTE.—ATOMS (Fig. 47) have an average diameter of about one *one-thousand-millionth* ($1/_{1,000,000,000}$) of an inch. A molecule of salt has a diameter of about one *ten-millionth* ($1/_{10,000,000}$) of an inch. The smallest particle of matter (Fig. 48) that can be viewed through a microscope has a diameter of about one *hundred-thousandth* ($1/_{100,000}$) of an inch. It is estimated that a cubic inch of air contains between 16 billion billion (16,000,000,000,000,000,000) and 16 thousand billion billion (16,000,000,000,000,000,000,000) molecules.

43. Neither The Molecules Which Form A Substance Nor The Atoms Which Form The Molecules Are In Contact With One Another.—Relatively large spaces intervene between neighboring atoms, and between neighboring molecules, even in the most compact of solid substances.

NOTE.—NOTWITHSTANDING THAT IMMENSE DISTANCES, CONSIDERED IN A RELATIVE SENSE, SEPARATE THE ATOMS WHICH FORM A MOLECULE, a mutual attraction, probably of an electric nature, still prevails among them. This mutual attraction will continue in force as long as the requisite number of atoms, to form the particular kind of molecule, are present, and no abnormal condition develops. The attraction may be strong or weak. If the latter, the molecules of a substance, if composed of different kinds of atoms, may be broken up by heat or by chemical or electrical means and then the different kinds of atoms may group by themselves to form molecules of the elemental substances (Table 42). Or, by similar methods, atoms may be added to the molecules of a substance, and another kind of substance be thereby produced.

44. The Molecule Is The Structural Unit By Which Substances Are Differentiated From One Another.—A molecule of water is composed (Fig. 46) of *two atoms of hydrogen and one atom of oxygen.* The composition of water molecules, from these elements alone and in these proportions, is absolute and invariable. Hence, molecules so constituted differentiate water from all other substances. Similarly, a molecule of common salt is composed of *one atom of sodium and one atom of chlorine.* This, likewise, is an atomical arrangement, in the composition of salt-molecules, which is precise and unalterable. Therefore, in this particular composition and arrangement lies the inherent difference between common salt and all other substances.

Note.—The Number Of Atoms In A Molecule may be few or many. Thus, each common-salt molecule is composed of but 2 atoms, while each white-of-an-egg molecule is composed of about 1,000 atoms.

45. Motion Is An Attribute Of Molecules And, Probably, Also Of Their Component Atoms.—Upon this important concept is predicated much of our knowledge regarding heat phenomena. Whether or not the atoms within a molecule are in motion with respect to one another is not definitely known. The molecules are supposed to be in motion except at the theoretical absolute-zero temperature (Sec. 61), at which temperature they are supposed to become motionless.

Note.—Molecules May Follow Regular Paths Along Straight Or Curved Lines, or their movements may be very erratic and irregular. In the latter alternative, the movements of molecules may be compared to those of individuals rushing hither and thither in a panic-stricken throng, now colliding with one another and now recoiling from the impact.

Note.—The Speed Of A Hydrogen Molecule at 32° F. is about 1⅛ mi. per sec. or nearly 6,000 ft. per sec. Mercury molecules move at about 1⁄10 the speed of hydrogen molecules, or about 400 mi. per hr.

46. Æther Is The Name Given To That Which Fills All Universal Space Unoccupied By Matter.—It occupies the infinitesimal—though large as compared with the size of the molecules—spaces which intervene between the atoms and molecules of substances, as well as the inconceivably vast reaches of interstellar space. Nothing is definitely known regarding the precise nature of æther. It is believed to be devoid of weight. Being thus imponderable,—without sensible or appreciable weight—it cannot (Sec. 23) be regarded as matter.

Note.—The Spaces Between The Atoms And Molecules of compact substances, as *glass* and *steel*, are not large enough to permit ingress of air molecules. But, on the basis of the common-sense assumption that an absolute void can nowhere exist, there must be something within these spaces. This something is what is called *æther*.

Note.—According To Certain Later Theories It Is Claimed That There Is No Æther.—It is said to have been proved by Einstein's theory of relativity that there is no æther. But whether or not there is an æther depends upon the definition which is accepted for "æther"— upon the properties which this hypothetical æther is assumed to possess. Various definitions and properties have been proposed for the æther. As a matter of common sense there must be something, in the space of the universe which is not occupied by atoms, whereby light waves, heat waves, electric waves, and magnetic waves are transmitted. (The scientists are reasonably certain that these waves can be readily transmitted through a perfect vacuum.) It is inconceivable that these waves —or any wave motion—can be propagated through "nothing at all." Hence, in this book the æther will be considered as that medium or something which fills what would otherwise be voids in space and whereby light, heat, electric, and magnetic waves are transmitted. Furthermore, since Einstein's theory of relativity does not affect the study of heat phenomena, it may for the present purposes be assumed that the statements herein given concerning æther are true.

47. Matter Is Indestructible.—The molecular composition of a portion of matter may be changed. Through new combinations of its elemental atoms the substance of which any portion of matter is formed may be changed into some other kind of substance. Or it may be changed into several other kinds of substances. But the precise quantity (and mass—see note below) of that particular portion of matter will continue undiminished.

NOTE.—IF SEVERAL SUBSTANCES BE COMBINED CHEMICALLY, the weight of the resultant substance will be the sum of the weights of the individual substances. A quantity of oxygen may unite with the combustibles in a lump of coal to produce combustion thereof. The combustibles will volatilize and disperse in gaseous form, leaving a residue of ash and clinker. But if these constituents—the gases and residual substances—could be reassembled, their combined weight would equal precisely the weight of the original lump of coal plus the weight of the oxygen which was supplied for its combustion.

48. Matter Cannot Be Created.—Hence the quantity of matter in the universe must be constant. It cannot be increased, neither can it be diminished. It may, however, undergo many changes of form.

EXAMPLE.—*Rags, wood, and certain other substances*, will, after undergoing certain mechanical and chemical processes, reappear as *paper*. *Hydrogen* and *oxygen* will, under certain conditions, combine and form *water*. Note that in both examples no *new matter* has been created. All that has occurred is that the form of existing matter has been changed.

49. There Are Three States Of Matter: (1) *Solid.* (2) *Liquid.* (3) *Gaseous.*—Theoretically, any substance, as *water* (Fig. 49), may, under different conditions, exist in each of these three states. As will be explained in following Secs. 225 and 351, *a substance in the gaseous state may be either a vapor or a gas.* In general, if the certain temperature and pressure conditions to which a given gaseous substance is subjected are such that the substance is then "near" the liquid state, it is then, under those conditions, called a vapor. If the certain conditions are such that the gaseous substance is "far away" from the liquid state then, under these conditions, it is called a gas.

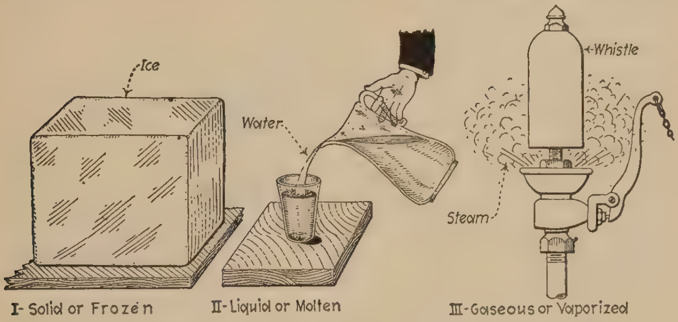


Fig. 49.—Illustrating the three states of matter—water in this case.

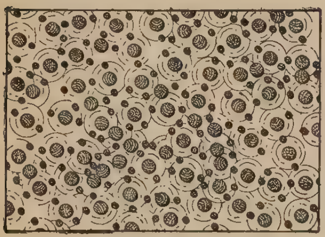


Fig. 50.—Imaginary condition of molecules in a solid (ice) magnified many millions of times.

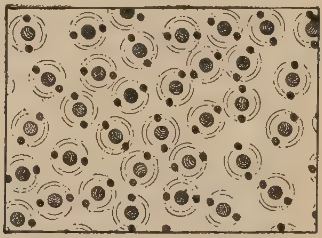


Fig. 51.—Imaginary condition of molecules in liquid (water) magnified many millions of times.

Note.—Figs. 50, 51, and 52 Illustrate Imaginary Arrangements suggested by the apparent action of atoms and molecules. The intervening distances are not proportional to the sizes of the atoms and molecules as illustrated. The actual proportional distances are, in a practical sense, immeasurably greater than appears in the illustratoins.

NOTE.—RESISTANCE TO CHANGES OF SHAPE IS A COMMON CHARACTERISTIC OF SUBSTANCES IN THE SOLID STATE.—The shape of a *piece of steel* (Fig. 53) is difficult to change. The shape of a *sheet of thin paper* is changed with relatively little difficulty. The paper may be folded with apparent ease. But its resistance to folding will, nevertheless, be definite and distinct.

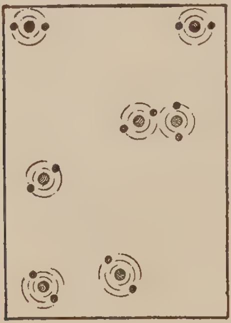


FIG. 52.—Imaginary conditions of molecules in gas (steam or water vapor) magnified many millions of times.

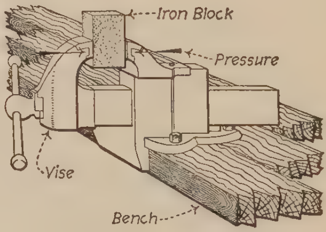


FIG. 53.—Solids resist compression.

Resistance To Compression And Susceptibility To Changes Of Shape Are Common Characteristics Of Substances In The Liquid State.—*Water* is practically incompressible. It will, however, instantly take the form of (Fig. 54) of any container in which it is placed.

Susceptibility Both To Compression And Changes Of Shape Are Common Characteristics Of Substances In The Gaseous State.—Gaseous substances, as *air*, *saturated steam*, which is a vapor, and *highly-superheated steam*, which approximates a perfect gas, tend to expand indefinitely when released from a container.

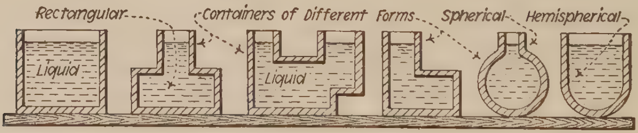


FIG. 54.—A liquid assumes the form of any container in which it is placed.

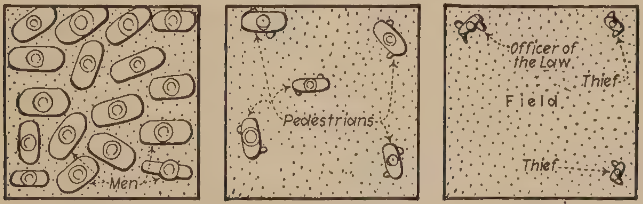
50. The Existence Of A Portion Of Matter In The Solid, Liquid, Or Gaseous State Depends On The Motion Of Its Molecules (Figs. 50, 51 and 52). As stated in Sec. 45, molecules move or vibrate. The state of the matter—solid, liquid, or gaseous—is determined by the rapidity and extent of motion of its molecules. In other words, as will be shown, the state of a given portion of matter is determined by the amount of heat—heat energy—which it contains.

Explanation.—"*In solids* the component molecules are in some way so closely bound together, and their vibrations, though still taking place, are so narrowly and rigidly limited in relation to one another, that the external form of the aggregation—the body taken as a whole—is capable of resisting the action of forces of considerable magnitude which may tend to deform it.

In liquids the molecules, though still held together by a mutual attraction which limits their distance of separation (in so far as internal molecular forces are concerned), they are now quite free to assume any position relatively to one another which they choose, or to *roll* about one another. This rolling is what we call *flow.*

In the gaseous form the molecules are very much more widely separated than in liquids or solids; they are more actively in vibration, and they tend to separate to the widest possible degree permitted by external resistances, such as the walls of a containing vessel." (From Reeve's Thermodynamics of Heat-engines.)

Note.—In Solids The Molecules Are Thought To Vibrate At A Comparatively Slow Rate and through a small range. Each molecule is analogous to a man (Fig. 55-*I*) in a densely-packed crowd. He may turn around and move slightly from side to side and backward and forward. But he cannot move far from one position, because he is resisted on all sides by other people.



I-Analogy to Molecules in a Solid

II-Analogy to Molecules in a Liquid

III-Analogy to Molecules in a Gas

Fig. 55.—Molecules of substances in the three states act like men in a crowd, pedestrians in a street, and thieves fleeing from an officer of the law. (This is a view from above.)

In liquids, the molecules vibrate more rapidly and through much wider ranges. Each molecule moves to and fro encountering little resistance. Molecules of liquids are analogous to individuals (Fig. 55-*II*) passing one another on a busy city square. They collide only occasionally.

In gases, the molecules are so far apart that they have little cohesive attraction for one another. They fly about very rapidly and freely.

They may be thought of as acting like thieves (Fig. 55-*III*) scattering through a field to escape pursuers. Because of their great freedom of movement and high velocities they bombard the sides of the containing vessel. This creates therein what is called a "pressure," (see Sec. 227).

Note.—The Molecules Of Different Portions Of Solid Matter Are Incapable Of Intermingling.—This is due to their restricted vibratory motion. Blocks of metal (Fig. 56) may be forced in contact with each other under enormous pressure, but no intermingling of the molecules of the two blocks will generally occur.

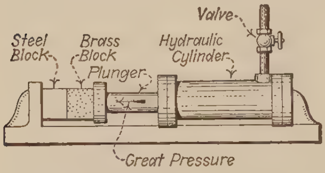


Fig. 56.—Solids remain to themselves, *i.e.*, do not mix, even when subjected to great pressure.

The Molecules Of Different Portions Of Liquid Matter May, Usually, Mingle Freely. This is due to their fluid motion. Fluidity is apparent in the facility with which a quantity of milk, when poured into a cup of coffee, permeates the entire mass. Similarly a drop of red ink in a glass of water will tint uniformly all of the water.

The Molecules Of Different Portions Of Gaseous Matter Will Mix Unrestrainedly. This may be observed in the blending of colors which attends the forcing of differently colored gases into a common vessel.

51. Molecules Behave Differently In The Three Different States In Which Matter Occurs.—That is, their behavior (as is explained later, Sec. 52) is determined by the amount of heat—heat energy—which is contained in the substance which they compose. The rigidity of a solid substance is due to the relatively strong mutual attraction which prevails among its molecules. The fluidity of a liquid substance is due to the relatively weak mutual attraction which prevails among its molecules. The volatility of a gaseous substance is due to the lack of cohesive force between its molecules. The molecules of an unconfined gas tend to disperse through all surrounding space. All trace of an unconfined gas may thus be lost.

Note.—The Attraction Among The Molecules Of A Solid is analogous to that which exists between two magnets (Fig. 57) in close proximity. The magnets will offer quite appreciable resistance to further separation. They will likewise resist a force tending to produce a sidewise movement of one relative to the other.

The Attraction Among The Molecules Of A Liquid may be compared to the weakened mutual attraction which the magnets in Fig. 57 would exhibit if a space equal, say, to their own length intervened between them.

The Freedom Of The Molecules Of A Gas is analogous to that which exists (Fig. 58) between the lead balls of an exploding shrapnel shell. The balls scatter unrestrainedly in all directions at first. Later, of course, they all fall to the earth.

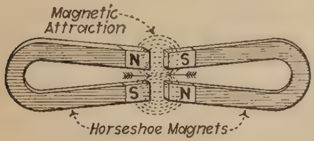


Fig. 57.—Molecules have attraction similar to that of magnets.

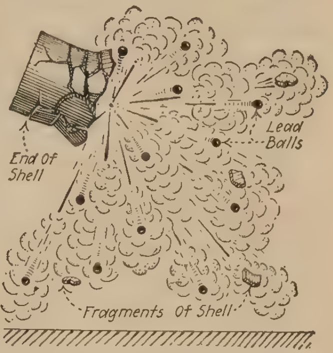


Fig. 58.—The freedom of movements of the lead balls from an exploding shrapnel shell illustrates the freedom of motion of gaseous molecules.

52. The State Or Condition Of Molecular Vibration And Separation Is Called Heat.—Heat is thus conceived to be an inherent attribute of matter so long as molecular vibration continues (Sec. 50). An *addition of heat*—heat energy—means either an *increase in molecular-vibration velocity* (kinetic heat energy) or an *increase in molecular separation* (potential heat energy) or both. When we say that heat has been added to a portion of matter, we actually mean that the vibration velocity of the molecules of the matter or the distance between the molecules has been increased through some external agency. Kinetic or potential energy has been added to the portion of matter. Conversely, when we say that heat has been abstracted from a portion of matter, we actually mean that the rate of vibration of the molecules of the matter or the distance between the molecules has been decreased (that heat energy has been abstracted) through some external agency.

53. The External Evidences Of Heat Transfer are, when heat is added, an enlargement or expansion (Sec. 185) and, when heat is abstracted a diminishment or contraction of the apparent bulk or body of the portion of matter. These indicate that, when an object is heated, the molecules spread farther apart on the average, due to their more rapid vibration. When the body is cooled their less rapid vibration permits their mutual attraction to pull them closer together. (See Sec. 54, for the principal effects of heat transfer.)

NOTE.—AGITATION OF A SUBSTANCE SPEEDS UP THE MOTION OF ITS MOLECULES.—If a soft wire (Fig. 59) be bent rapidly back and forth, the bent portion of its bulk will become heated. This will be due to the agitation of the molecules in the bent portion. If a piece of lead (Fig. 60) be hammered, its temperature will rise. This will be due to the molecules having been jarred, slipped and agitated. The rubbing together (Fig. 61) of substances agitates the molecules and causes increase of heat. Agitation of liquids and gases causes heat to develop therein.

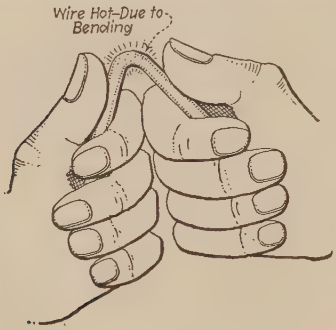


FIG. 59.—Bending wire agitates the molecules, hence makes it hot.

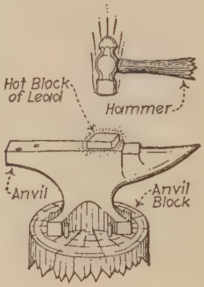


FIG. 60.—Lead becomes hot when hammered.

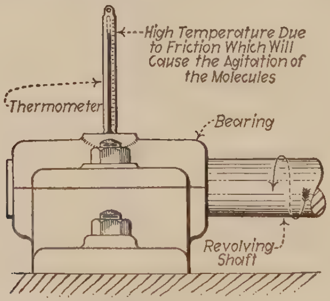

High Temperature Due to Friction Which Will Cause the Agitation of the Molecules
Thermometer
Bearing
Revolving Shaft

FIG. 61.—A bearing heats because the molecules are made to vibrate more rapidly by the rubbing of the metal surfaces.

54. Broadly, There Are Only Three Possible Effects Of Heat Transfer To Or From Any Substance—any one, two, or all three of which may be produced, depending on the conditions under which the heat transfer takes place, as is explained in Sec. 96: (1) *Change in temperature of the substance* (Sec. 55) or in molecular vibrational velocity; the part of the total heat which produces this change is called "*vibration heat.*" (2) *Change in state* (Sec. 49) or in the molecular-attraction forces; the part of the heat which produces this change is called "*disgregation heat.*" (3) *External work* or change in molecular position against external forces; the part of the total heat which produces this change is called "*external-work heat,*" or "external heat." Of course there is really only one kind of heat; the terms "vibration heat," "disgregation heat," and "external-work heat" are employed merely to designate how portions of the total heat which is transferred to a substance are expended in different ways.

EXAMPLE.—Consider the effects of adding heat to a quantity of water confined in a metal cylinder (as in Fig. 62) under a piston, *P*, and a weight, *W*. The heat which is first added goes almost entirely, as would be indicated by a thermometer, toward *raising the temperature* of the water; this would then be *vibration heat.* The water would also expand, as indicated at *II* (Fig. 62) but the expansion would be very small. Hence very little of the added heat is *external-work heat,* useful in lifting the weight, *W*. But, after continued heating, the water would reach a point (temperature) where it would become no "hotter;" that is, its temperature would cease to rise. The heat which is then added (*III*, Fig. 62) separates the molecules of the water against their mutual attractive forces and against the weight, *W*, which tends to hold them together. Hence, the heat which is now added is partly *disgregation heat,* which is

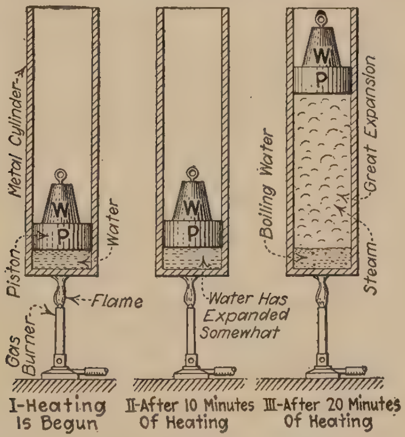
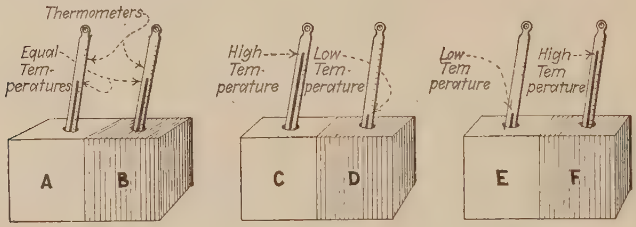


FIG. 62.—Illustrating effects of heating water.

useful in changing *the state* of the substance (from water to steam), and is partly external-work heat which is useful in *doing external work* (by lifting the weight, *W*, against the force of gravity).

55. The Temperature Of A Body (Figs. 63 and 64) is a measure of the tendency of that body to transmit heat to (Fig. 63) or to withdraw heat from another body. The *temperature* of any substance *is a measure of the kinetic or vibrational energy* of its *individual* molecules—not the total kinetic energy of all of its molecules taken together, for this a measure of its heat energy or heat content. Hence, do not confuse *temperature* with *heat. Temperature* is *intensity* of heat. Temperature describes the degree of hotness or coldness of a body. Temperature may be thought of as the pressure of the heat in a body. Just as the pressure indicated by a steam gage is no indicator of the total quantity of steam which the boiler or boilers contain, so the temperature of a body (indicated by a thermometer) is no measure of the total amount of heat contained in the body.



I-No tendency for heat transfer

II-Tendency for heat transfer from C to D

III-Tendency for heat transfer from F to E

Fig. 63.—The temperature indicates the tendency of a body to transfer heat.

Note.—In General, It May Be Stated That Temperature Is An Approximate Measure Of The Amount Of Heat Per Unit Weight which a given material contains. In general, the more heat—heat energy a given body contains the higher will be its temperature. But, this principle does not hold at or near temperatures where changes of state (Sec. 49) occur. Hence, the temperature of a substance is not, necessarily, any indication whatsoever of the amount of heat which the substance contains. The heat content may, when a change of state is occurring, be increased or decreased and yet the temperature remain constant (Sec. 103). For example, water at its boiling temperature—during a change from the liquid to the vaporous state—may have (Sec. 52) much heat added to it and the water be thereby converted into steam;

without change in the temperature. The steam has the same temperature (Sec. 104) as the boiling water.

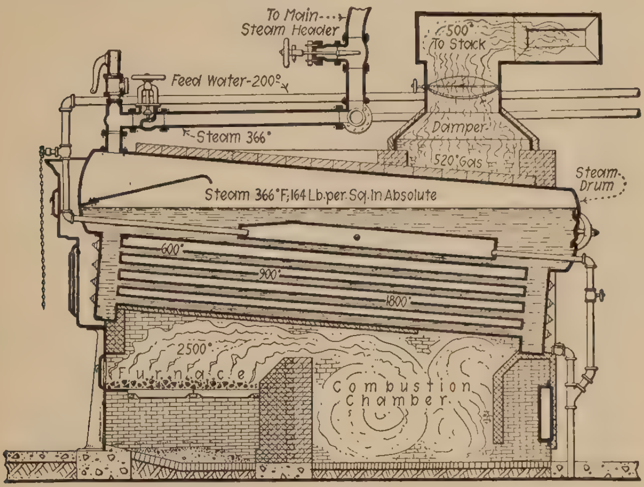


FIG. 64.—Showing how the temperature—the ability to transfer heat—of boiler gases decreases along the flue-gas path. (The temperatures indicated above are approximately those which should be maintained in a horizontally-baffled water tube boiler. *Brown Instrument Co.*)

NOTE.—TEMPERATURE IS REALLY THERMAL HEAD OR PRESSURE.—Temperature is to heat what voltage is to electricity. Where there is no difference in temperature, there can be no flow of heat (O. B. Goldman).

EXAMPLE.—Fig. 64 shows the temperatures which should be maintained for the efficient operation of a modern horizontally baffled water-tube boiler.

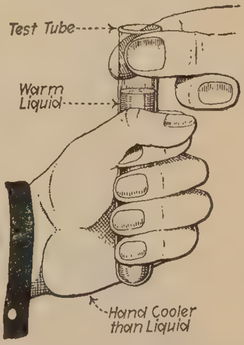


FIG. 65.—To cool (slightly) a hot test tube and contents, hold in relatively cool hand.

56. "Cold" Is A Term Used To Express A Condition Of Temperature. It is often thought of as the opposite of heat. But it is not. In fact, *cold* is merely a word used to designate the relative condition of a substance when it has less than the normal *intensity* of heat. Therefore, to render a body cold, (Fig. 65) it is merely necessary to take some heat away from it—not to add *cold* to it. In general, a "cold" body is merely one which has a temperature lower than that which is considered as the usual, normal, or ordinary temperature.

57. The Instruments Ordinarily Used For Measuring Temperature Are Called Thermometers (see also Sec. 652 Div. 19).—In its simplest form (Fig. 66) a thermometer is a hollow glass tube, hermetically sealed at both ends, and expanded into a bulb at its lower end. The bulb is filled with a suitable liquid, as mercury, and all air is exhausted from the tube before it is sealed. This is to permit free expansion of the liquid to the top of the tube. When the bulb is heated the liquid expands (Sec. 185) and rises in the tube. When the bulb is cooled the liquid contracts and lowers in the tube. When a proper scale is used in connection with this arrangement, the temperature of surrounding materials may be accurately determined. Other instruments for measuring temperature are further discussed in Div. 19.

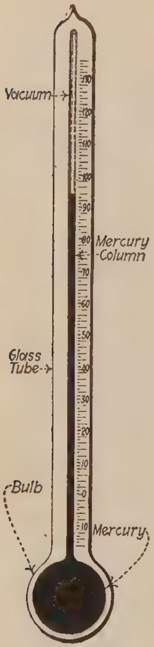


Fig. 66.—Mercury thermometer.

Note.—An Early Type Of Thermometer is illustrated in Fig. 67. A glass tube, with a large bulb on one end, was heated. The tube was then inverted and the open end inserted in a vessel of colored water. In cold weather, the air in the bulb con-

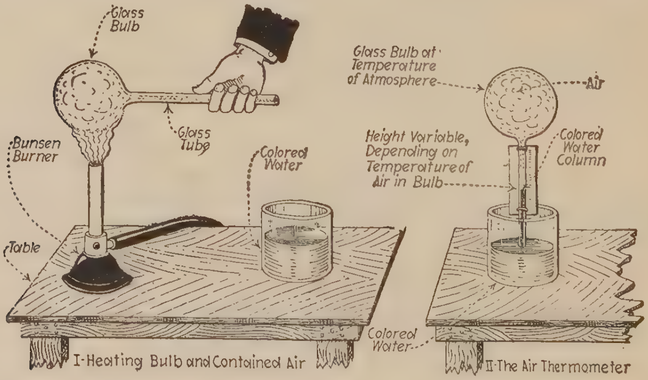

Glass Bulb
Glass Tube
Bunsen Burner
Colored Water
Table
I-Heating Bulb and Contained Air
Glass Bulb at Temperature of Atmosphere
Air
Height Variable, Depending on Temperature of Air in Bulb
Colored Water Column
Colored Water
II-The Air Thermometer

Fig. 67.—Making an air thermometer.

tracted. The colored water was thus forced up in the stem by the external air pressure. In warm weather the water-column was correspondingly low. By placing a scale beside the tube, it could thereby be known when the temperature was high or low. Obviously, this thermometer was not suitable for showing temperatures below the freezing point of water.

58. Thermometric Scales Are Series Of Graduated Divisions (Fig. 68) which are marked on the tubes or stems of thermometers, or upon separate flat surfaces set adjacent to the stems. By means of such scales, the temperatures are read directly from the instruments in "degrees" (Sec. 59).

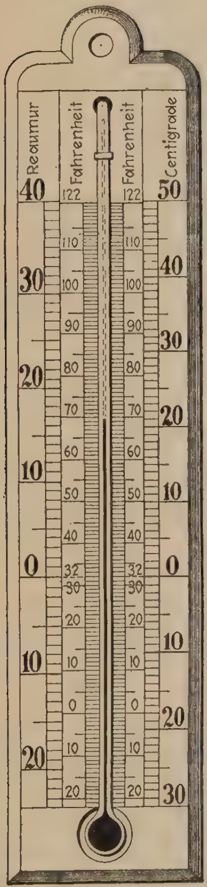


Fig. 68.—Thermometer with 3 scales.

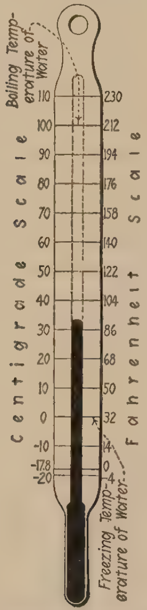


Fig. 69.—Fahrenheit and Centigrade scales compared.

59. There Are Three Thermometric Scales In General Use (Fig. 68).—(1) *The Fahrenheit scale.* (2) *The Centigrade scale.* (3) *The Reaumur scale.*

The Fahrenheit scale is in popular and engineering use in English-speaking countries. The Centigrade scale is in popular use in most European countries. It is the world-wide standard in all scientific usage. The Reaumur scale is used principally in Russia.

NOTE.—THE FAHRENHEIT THERMOMETRIC SCALE (Fig. 69) was invented by Gabriel Daniel Fahrenheit, of Danzig, Germany, in 1714. Fahrenheit assumed that the temperature of a mixture of equal weights of snow and sal-ammoniac (ammonium chloride) was the lowest obtainable. Therefore, he accepted this as the zero (0) of temperature. The blood-temperature of the human body, as shown by the rise of the mercury in the column, was then selected as marking another definite point in the scale and called—incorrectly, see below—100. The distance between these points was divided into 100 equal spaces. Each space was called a degree (°) of temperature. According to this scale, water boils (under atmospheric pressure) at 212° and freezes at 32°. The scale between these temperatures is, therefore, divided into $212 - 32 = 180$ equal spaces or degrees. One degree of temperature, Fahrenheit (1° F.), is indicated by $\frac{1}{180}$ of the expansion of the mercury column of a thermometer which occurs when the temperature is raised from that of freezing water (or melting ice) to that of boiling water. The actual blood temperature is now known to be 98.6° F. Its non-agreement with Fahrenheit's 100° blood temperature is due to errors in the original experiments.

NOTE.—THE CENTIGRADE THERMOMETRIC SCALE (Fig. 69), or *Celsius scale*, as it is sometimes called, was invented by the Swedish physicist Celsius. The freezing and boiling temperatures of water were taken as definite limits of gradation. The height of the column of mercury at the freezing temperature was designated the zero-degree point of the scale. Also, the height of the mercury column at the temperature at which water boils was designated as the 100° point of the scale. The height of the mercury column between the freezing point and the boiling point was then divided into 100 equal spaces, each called a degree.

60. The Calibration Of A Centigrade Thermometer (Fig. 70) see also Sec. 659, consists in determining the 0°-mark by placing the thermometer in melting ice (Fig. 70, *I*) and marking the height of the mercury column when it is at that temperature. The thermometer is then placed in steam coming from boiling water (Fig. 70, *II*). The 100°-mark is placed even with top of the mercury when it is at the temperature of this steam. The distance between the 0°-mark and the 100°-mark is divided into 100 equal spaces. The rise of the top of the mercury column for a distance equal to one space, indicates a temperature rise of one degree Centigrade (1° C.).

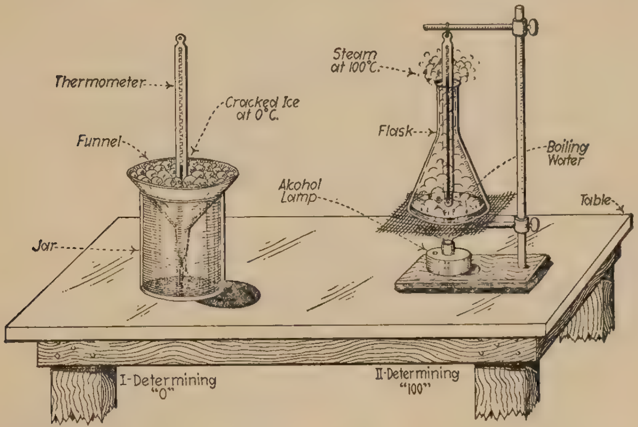


Fig. 70.—Determining 0 and 100-degree marks on a Centigrade thermometer.

61. The Absolute Thermometer Scale (Fig. 71) must be used in certain calculations concerning the thermal action of some substances, particularly gases. In order to describe this scale it is necessary to consider *absolute zero* (0° *abs.*) which is the lowest temperature theoretically attainable. It will be recalled (Sec. 52) that heat is a condition of motion of molecules. If it were possible to have a substance in such a state that the molecules were motionless, there certainly would be no kinetic heat energy in the substance and its temperature would then be the lowest possible to obtain. When a perfect gas, which is confined in a vessel, at 0° C. is cooled 1° C., its pressure is observed to decrease 1/273 of the pressure at 0°. Since the pressure exerted by a gas is due to bombardment of the walls of the containing vessel by the vibrating

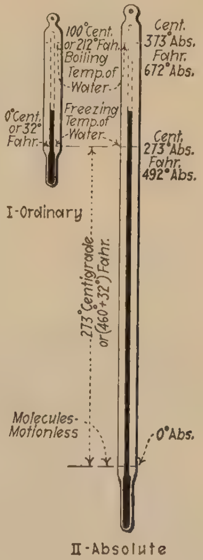


Fig. 71.—Ordinary and absolute thermometer scales compared.

molecules, it is concluded from the above observation that if the temperature were lowered 273° C. below 0° C., there would then be no pressure exerted by the molecules. There would be absence of all heat. The temperature of a substance at this theoretically lowest temperature is assumed to be 0° *on the absolute scale.* The water freezing temperature is, then, 273° C. *abs.* (Fig. 71) and the boiling temperature of water is at 373° C. On the Fahrenheit scale, absolute zero is 492° *abs.* below the freezing point of water which is 32° F., hence, 0° F. is equivalent to 460° F. *abs.*

NOTE.—A METHOD OF MANUFACTURING A THERMOMETER (Fig. 72) follows: A glass tube with capillary opening and a bulb blown at one end (*I*) is filled with mercury. The bulb and contained mercury are heated (*II*) to a temperature somewhat higher than that for which the thermometer is to be used. While at this temperature the tube is sealed off—closed—(*III*) at its open end. When the tube, bulb, and mercury cool, the mercury contracts (*IV*) and leaves the tube empty in the upper portion. Thus, there is a vacuum above the mercury column.

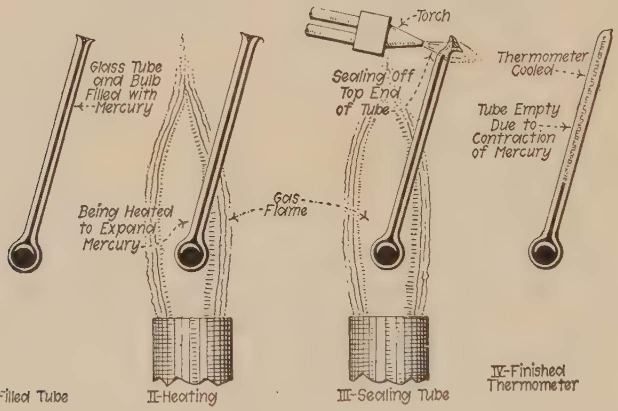

Torch
Glass Tube and Bulb Filled with Mercury
Sealing Off Top End of Tube
Thermometer Cooled
Tube Empty Due to Contraction of Mercury
Gas Flame
Being Heated to Expand Mercury
I-Filled Tube
II-Heating
III-Sealing Tube
IV-Finished Thermometer

FIG. 72.—Steps in making a thermometer.

62. Readings Of One Thermometer Scale May Be Converted To Equivalent Readings Of Another Scale.—It is often necessary in practice to make such conversions. Fig. 68 illustrates a thermometer with three scales, thus it is possible to read temperature from it in any one of the three, but usually thermometers are graduated for one scale only. Following are facts and rules used for converting readings from one scale to another.

(16) $1°\ C. = \frac{9}{5}°\ F. = 1.8°\ F.$

(17) $1°\ F. = \frac{5}{9}°\ C. = 0.555°\ C.$

Rule 1.—To Reduce Temperatures As Shown On The Fahrenheit Scale To The Centigrade (Fig. 73), find the number of degrees Fahrenheit above the freezing temperature of water and multiply by $\frac{5}{9}$. By formula:

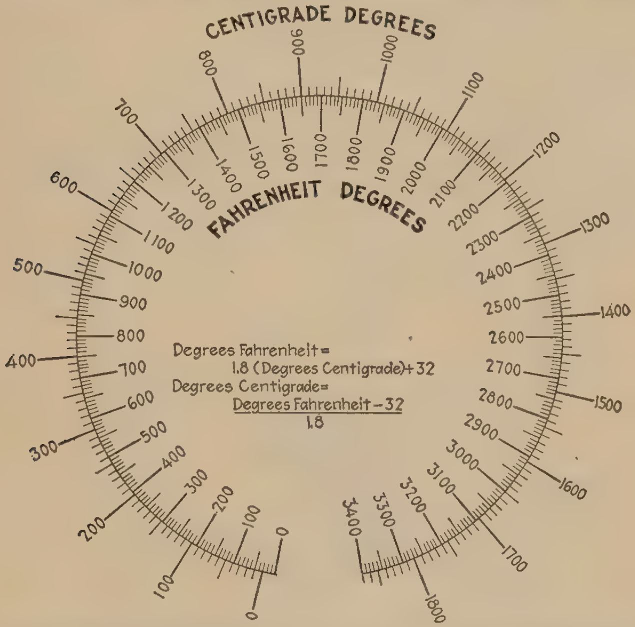


Fig. 73.—Chart showing relation of Fahrenheit to Centigrade degrees. (*W. S. Rockwell Company.*)

(18) $$T_C = \frac{5}{9}(T_F - 32) \qquad \text{(deg. Cent.)}$$

Wherein: T_C = degrees on Centigrade scale. T_F = degrees on the Fahrenheit scale.

Rule 2.—To Reduce Temperatures As Shown On The Centigrade Scale To The Fahrenheit, multiply the numbers of degrees Centigrade by $\frac{9}{5}$ and add 32. By formula:

(19) $$T_F = \frac{9}{5}T_C + 32 \qquad \text{(deg. Fahr.)}$$

Wherein T_F and T_C have the same meanings as in For. (18).

NOTE.—TO CONVERT A THERMOMETER READING TO ABSOLUTE SCALE Centigrade, add 273 to the Centigrade reading. To convert a Fahrenheit reading to absolute temperature Fahrenheit, add 460 to the Fahrenheit reading. (The value 460 is not exact but is very nearly so.) These rules may be expressed by the following formulas:

(20) $\mathbf{T}_F = T_F + 460$ (deg. Fahr. abs.)

(21) $\mathbf{T}_C = T_C + 273$ (deg. Cent. abs.)

Wherein: $\mathbf{T}_F$ and $\mathbf{T}_C$ = the absolute temperatures measured in Fahrenheit and Centigrade degrees, respectively. T_F and T_C = respectively, the Fahrenheit and Centigrade temperatures.

EXAMPLE.—A Fahrenheit thermometer records 180°. What is the equivalent Centigrade reading? SOLUTION.—By For. (18), $T_C = \frac{5}{9}(T_F - 32) = \frac{5}{9} \times (180 - 32) = 82\frac{2}{9}°\ C.$

EXAMPLE.—A Centigrade thermometer records 51 degrees. What is the equivalent Fahrenheit temperature? SOLUTION.—By For. (19), $T_F = \frac{9}{5}T_C + 32 = [\frac{9}{5} \times 51] + 32 = 123\frac{4}{5}°\ F.$

EXAMPLE.—The temperature of a solution (Fig. 74) is 20° C. What would a Fahrenheit thermometer read in the same solution? SOLUTION. By For. (19), $T_F = \frac{9}{5}T_C + 32 = [\frac{9}{5} \times 20] + 32 = 36 + 32 = 68°\ F.$

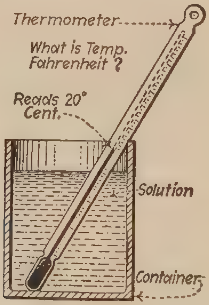


FIG. 74.—What is the Fahrenheit temperature?

EXAMPLE.—A certain solution solidifies at 9° below zero Fahr. (−9°F.). What is the equivalent temperature by a Centigrade thermometer? SOLUTION.—By For. (18), $T_C = \frac{5}{9}(T_F - 32) = \frac{5}{9} \times (-9 - 32) = \frac{5}{9} \times (-41) = -22\frac{7}{9}°\ C.$, or $22\frac{7}{9}°$ *below zero Cent.*

EXAMPLE.—A temperature of 32° F. is equivalent to 32 + 460 = 492° F. *absolute* (abbreviated *abs.*). A temperature of 550° F. is equivalent to 550 + 460 = 1,010° F. *abs.*

EXAMPLE.—A certain solution at a certain pressure boils at 20° C. What is the absolute temperature in 8 degrees Centigrade at which the solution boils? SOLUTION.—By For. (21), $\mathbf{T}_c = T_c + 273 = 20 + 273 = 293°$ *C. abs.*

63. Table Showing Temperatures At Which Some Important Phenomena Occur.—The melting and boiling phenomena here listed occur at the temperatures shown only when the substances are heated at normal atmospheric pressure.

Temperature		Phenomena	Temperature		Phenomena
Deg. Cent.	Deg. Fahr		Deg. Cent.	Deg. Fahr.	
3,500	6,330	Temp. of electric arc.	288	550	Gunpowder ignites.
3,500	6,330	Carbon vaporizer.	215	420	Tin melts.
3,000	5,400	Attained by Thermit.	109	228	Sulphur melts.
2,800	5,072	Oxyacetylene flame.	100	212	Water boils.
2,500	4,532	Oxmium melts.	79	174	Alcohol boils.
2,225	4,037	Iridium melts.	65	149	Fusible alloy melts.
2,231	4,000	Bessemer furnace.	61	142	Beeswax melts.
1,710	3,080	Platinum melts.	46	114	Paraffin melts.
1,530	2,731	Wrought iron melts.	44	111	Phosphorous melts.
1,400	2,552	White "heat."	36.8	98	Human body in health.
1,371	2,500	Steel melts.	17	62	Mean temperature of sea.
1,200	2,192	Orange red "heat."	0	32	Water freezes.
1,100	2,012	Copper melts.	−17.7	0	Mixture salt and ice melts.
1,063	1,981	Pure gold melts.	−38.8	−34.3	Mercury freezes.
1,050	1,922	Cast iron (lowest) melts.	−55	−68	Temp. in Arctics.
970	1,778	Silver melts.	−70	−94	Balloon (9 miles high).
700	1,292	Dull red "heat."	−118	−180	Ether freezes.
625	1,157	Aluminum melts.	−252	−422	Hydrogen boils.
405	762	(About) coal ignites.	−259	−434	Hydrogen freezes.
400	752	Red hot iron visible in dark.	−270	−454	Greatest Artificial "cold" (1908).
357	674	Mercury boils.	−273	−460	Absolute zero.
316	600	Lead melts.			

64. Table Showing Equivalent Temperature Readings For Fahrenheit And Centigrade Scales.

Deg Fahr.	Deg. Cent.	Deg. Fahr.	Deg. Cent.	Deg. Fahr.	Deg. Cent.	Deg Fahr.	Deg. Cent.
−40	−40	95	35	230	110	365	185
−31	−35	104	40	239	115	374	190
−22	−30	113	45	248	120	383	195
−13	−25	122	50	257	125	392	200
− 4	−20	131	55	266	130	401	205
5	−15	140	60	275	135	410	210
14	−10	149	65	284	140	419	215
23	− 5	158	70	293	145	428	220
32	0	167	75	302	150	437	225
41	5	176	80	311	155	446	230
50	10	185	85	320	160	455	235
59	15	194	90	329	165	464	240
58	20	203	95	338	170	473	245
77	25	212	100	347	175	482	250
86	30	221	105	356	180	491	255

QUESTIONS ON DIVISION 2

1. What is matter? How may it be recognized?
2. Name ten substances made of matter.
3. Of what is matter made up? Is this the smallest particle of matter?
4. What is an element? How many elements are known?
5. Name some common elements.
6. Of what is the atom composed?
7. Are atoms and molecules in contact? What holds them together?
8. What is the determining feature in the makeup of matter? What determines whether a substance is wood or iron?
9. Do molecules and atoms move? How?
10. How many times larger than a molecule of salt is the smallest particle that is visible under a microscope?
11. What is between atoms and molecules? Why no air?
12. Can matter be destroyed? Created?
13. In what three states is matter found? Describe briefly the condition of a substance in each state.
14. How do molecules behave in the three states?
15. Are molecules closer or further apart in a gas than in a solid?
16. What causes molecules to vibrate? What is heat?
17. What is temperature? Is the temperature an indication of the contained heat?
18. What is cold?

19. Is feeling a good way to judge temperature? Why?

20. How is temperature accurately measured?

21. Describe the Fahrenheit thermometer scale. The Centigrade.

22. What is the absolute thermometer scale? Explain.

23. What relation exists between Fahrenheit degrees and Centigrade degrees?

24. What is the rule for converting temperature readings on the Fahrenheit scale to the Centigrade scale? Vice versa?

25. How are ordinary thermometer readings reduced to absolute readings?

PROBLEMS ON DIVISION 2

1. Mercury boils at a temperature of 357° C. What is the equivalent temperature on the Fahrenheit scale?

2. Frozen ammonia is found to melt at −75.5° C. What is the equivalent temperature by a Fahrenheit scale?

3. Pure iron melts at about 2,750° F. What will a temperature recording instrument with a Centigrade scale record when inserted in the newly melted iron?

4. Hydrogen gas has been liquified at the very low temperature of −396.4° F This is noticed to be near the temperature of absolute zero. What is the temperature by the Centigrade system of measuring temperature?

5. Express the following in absolute temperatures Fahrenheit: 212° F., 460° F., −32° F.

6. Express the following in absolute temperatures Centigrade: 100° C., 0° C., −175° C., 20° C.

DIVISION 3

THE SOURCE OF HEAT

65. Practically All Of The Earth's Heat Is Derived Either Directly Or Indirectly From The Sun.—It is this heat that insures continuance of all plant and animal life.

NOTE.—THE HEAT FROM THE SUN PROPAGATES PLANT LIFE UPON THE EARTH.—Eventually, the plants become available for use as fuel, either as coal (Fig. 75) or wood. Coal (Fig. 75) is formed from deposits of vegetable matter which have been subjected to great pressure and heat through long periods of time. Decay of vegetable and animal deposits within the earth also results in the formation of natural gas and mineral oil (Fig. 76). Such gas and oil are likewise available for fuel. The heat of the sun is stored up in these fossil fuels. Thus it is made indirectly available for mankind's use.

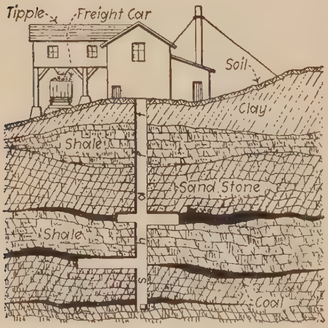


FIG. 75.—Section of a coal mine.

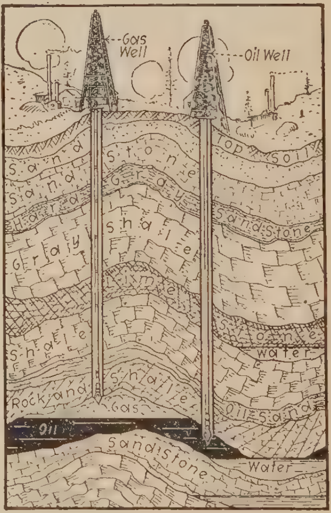


FIG. 76.—Section of earth showing gas and oil wells.

NOTE.—SMALL POWER PLANTS (Fig. 77) HAVE BEEN SO CONSTRUCTED AS TO DRAW THE HEAT NECESSARY FOR THEIR OPERATION FROM THE SUN.—But such plants are of very limited application. The power realized therefrom is, ordinarily, practically incommensurable with the relatively great cost and complication of the apparatus required. Also, the direct heat of the sun is not constantly available. In some climates, long intervals may elapse during which the sun is obscured by clouds.

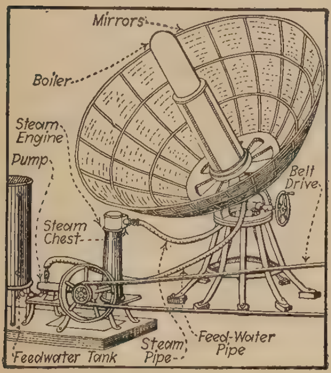


FIG. 77.

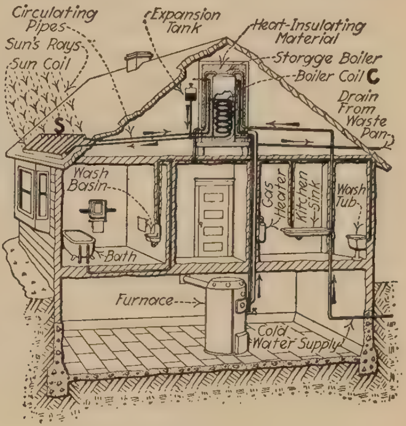


FIG. 78.

FIG. 77.—*Pifres* sun-power plant. (From *Smithsonian Report*, 1913.) (The mirrors are held in a reflector-shaped-frame unit which can be faced toward the sun. A hand wheel is used to rotate the unit to such a position that the sun's rays will fall directly on the mirrors. The rays from the sun then strike the mirrors and are reflected onto the boiler which is located in the center or "focus." The water in the boiler absorbs heat from the sun's rays and is thereby transformed into steam. The steam, thus formed, is used to drive the engine. The exhaust steam from the engine is used in a feedwater heater to heat the previously cold water which is pumped into the boiler.)

FIG. 78.—Showing installation for heating water for bathing and washing purposes. (*Day & Night Solar Heater Co.*, Los Angeles, Cal.) (The non-freezing liquid, shown in black, upon being heated in the sun coil, *S*, on roof, circulates through the coil, *C*, inside of the storage boiler, thus heating the water. Note that the warmed water, which is to be used, does not circulate through the sun coil, *S*.)

See also Fig. 78 which shows how the sun's rays are used directly for water heating in California.

66. Heat Rays From The Sun Cause Evaporation Of Water From Oceans, Lakes and Rivers.—The ascending vapors gather in the upper strata of the earth's atmosphere to form clouds. Eventually the vapors condense and descend again to earth, falling on hill and mountain in the form of rain. The rain flows in rivulets to larger streams and rivers. That water which falls on the higher parts of the earth's surface possesses potential mechanical energy. This may, with suitable equipment, be made available as mechanical or as electrical energy.

67. The Source Of Solar Heat has been investigated for many years. Several theories in explanation of its origin have been advanced. Probably the most satisfactory of these—the *nebular hypothesis*—is as follows:

Explanation.—It is assumed that the space now occupied by our planetary system was originally filled with a *nebula.* A nebula is believed by some to be an extremely tenuous body composed of unorganized gaseous matter whirling at an enormous speed around a common vortex or center. Others believe a nebula to be made up of *planetesmals* or particles of matter. Portions of this nebula separate from the parent mass. They gradually contract and cool during the course of ages. Eventually they formed the planets, planetoids, and other celestial bodies which comprise our present solar system of spheres—small and large—which revolve about the sun.

Coincidentally, the immense nebulous mass immediately adjacent to the vortex, or common center, (though extending thence in all directions through many millions of miles of space) was likewise contracting and solidifying into a compact body. This body is now known to us as *the sun.* The shrinking or contracting of the various portions of nebula has been due to the gravitational or attractive force of the particles which comprised the original mass.

68. The Contraction Of The Sun Converts Potential Energy Of Position Into Heat, just as the falling of a stone finally converts its potential energy of position into heat. It has been calculated that a contraction of the sun's diameter of about 250 ft. per year is sufficient to supply the heat which is given off by radiation. At this rate of contraction, 1,000 years would elapse before the sun would exhibit a sufficient alteration of size to be discerned through our telescopes. For a more complete discussion of this subject see Abbots' The Sun.

69. The Internal Heat Of The Earth Is Virtually Unutilized. The presence of this heat is evident from the volcanoes and hot springs that exist in certain localities. It is thought that the earth's crust may be 100 miles thick, and that beneath this crust the mass of the earth is molten hot.

Note.—The Earth's Internal Heat Is Utilized To Some Extent In Italy For The Development Of Power.—In certain volcanic regions powerful jets of superheated steam, of from 10,000 to 40,000 lb. per hr. capacity, and at pressures of from 30 to 75 lb. per sq. in., are obtained from borings in the earth. These borings are from about 8 to 16 in. in diameter and from 300 to 750 ft. deep. They are lined with steel tubes which convey the steam to the earth's surface where it is utilized in steam engines, steam turbines or similar energy-converting equipment.

70. Mechanical Energy, or Action, Produces Heat.—It cannot be said that mechanical action is a source of heat, since the heat so produced comes indirectly from the sun. Heat is a *manifestation of certain mechanical action.* Or, otherwise stated, *mechanical energy may be converted into heat energy.* Primitive man found that he could start a fire (Fig. 79) by rubbing sticks together. The rubbing together of pieces of wood causes heat, due to the friction between the pieces. The mechanical energy applied by the man is transformed into heat energy. The man and the wood are dependent upon the sun for existence. Hence, the sun is, indirectly the source of the heat generated in the rubbing process.

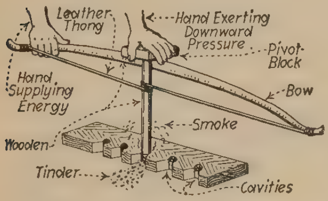


FIG. 79.—Fire from friction—kinetic energy transformed into heat energy.

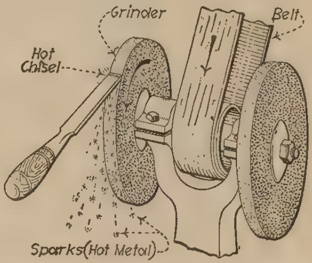


FIG. 80.—Heat from friction of chisel against moving grinder.

NOTE.—THE FORM OF FRICTIONAL HEAT THAT CHIEFLY CONCERNS THE POWER PLANT OPERATION is that which is manifested in the heating of engine and shaft bearings by reason of excessive load or inadequate lubrication.

EXAMPLES.—When an automobile, or a railway car, is stopped by applying the brake, considerable heat is developed by friction between the brake shoe and the wheel or other revolving element. The applied mechanical energy of the braking mechanism is converted into heat energy which is dissipated in the surrounding atmosphere. In grinding a tool (Fig. 80) on an emery wheel, or grindstone, heat is developed.

71. Heat Is Developed When The Physical Forms Of Bodies Of Matter Are Changed.—If mechanical energy is so applied as to change the shape of a body, heat is "generated." Lead becomes hot (Fig. 60) when hammered. The heat so manifested is due to percussion. When an iron wire (Fig. 59) is bent continuously back and forth at the same point, it becomes hot because of the repeated changing of its shape. When a gas is confined in a cylinder (Fig. 34) and is compressed by the piston's forcing it into a smaller space, the gas becomes very warm. It may, under certain conditions, become sufficiently hot to ignite spontaneously. This *heat due to compression* is noticeable in the action of a bicycle or automobile tire-pump and in certain types of gas-engines (Fig. 34). It results from the decreasing of the volume occupied by the gas.

Note.—Heat Developed In The Compression Of A Gas Is Transmitted through the wall of the containing vessel and may be carried away in a current of water or in the surrounding atmosphere. Then re-expansion of the gas must be attended by absorption of a quantity of heat, from surrounding substances, equal to the quantity of heat so dissipated. This principle is utilized in the mechanical refrigerating plant. An often-observed example of the result of this phenomena is the coating of frost which forms on the end of a pneumatic-rock-drill exhaust pipe when the drill is in operation.

72. Heat May Be Derived From Electrical Energy.—That is, electrical energy may be transformed directly into heat energy. Every conductor which is carrying a current of electricity offers resistance to the current. A current-carrying conductor always becomes heated to some degree, even though the heating may often be practically inappreciable. Such heating of a conductor represents a loss of electrical energy. This loss is known to the electrician as the I^2R-loss, wherein I represents the current in amperes and R the resistance of the conductor in ohms.

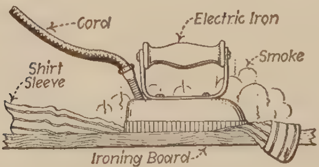


Fig. 81.—Heat from electrical energy.

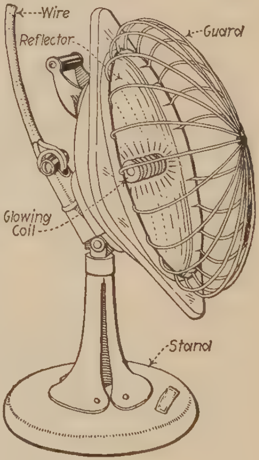


Fig. 82.—Heat from electrical energy.

Note.—The Heat Thus Developed In Electrical Conductors Is Made Useful In Various Ways.—Electric-furnaces, welding, car-heating, cooking, ironing (Fig. 81) are a few of the methods of utilizing electrically-developed heat. The electrical method of room heating (Fig. 82) offers many conveniences. It is, however, relatively expensive in most localities. Electricity, flowing through and heating to incandescence a metal filament, is now indispensable as a producer of light. While producing the light, the electric current also causes the white-hot incandescent-lamp filament to give off heat.

73. Heat Is Produced by Certain Chemical Reactions. That is, when certain chemical processes or reactions occur, chemical energy which resided in the substances involved in the reaction is transformed into and liberated as heat energy. Conversely, it is necessary to add heat energy to effect certain other chemical reactions; see Sec. 157 for a further discussion. Chemical reaction includes all forms of combustion. And combustion—burning—of fuels is the source of heat with which the power-plant operator is mainly concerned. The combustion or burning of coal (Fig. 83), wood, oil or gas (Fig. 84), is the chemical action (see Div. 14 on Combustion) occurring between the carbon and hydrogen, contained in the fuel substances, and the oxygen of the air.

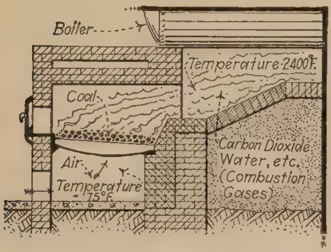


Fig. 83.—Combustion of coal—a chemical action.

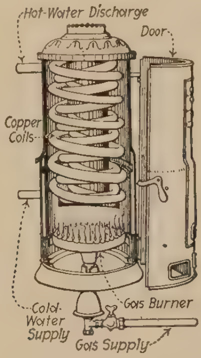


Fig. 84.—Combustion of gas heats water.

Note. The Respiration Of Animals Is A Process Of Slow Combustion Or Chemical Action. The oxygen breathed into the lungs combines with the carbon and other elements in the blood. The resulting chemical action liberates or "causes" *animal heat.*

74. The Elements Composing Fuel Substances Change Their Molecular Form In Uniting With Oxygen.—But nothing is lost (Sec. 48). Only the form is changed. This change is accompanied by a very violent action of the atoms in forming new molecules. It is so violent as to produce or liberate heat sufficient to cause the combustible substances to glow with a red or white light. This situation is explained more fully in Sec. 176. By combustion, the chemical energy (potential energy) of the fuel substance is converted into heat energy.

QUESTIONS ON DIVISION 3

1. What is mankind's main source of heat energy?

2. Why is the direct heat of the sun not commercially available as a source of power?

3. What is the relation between the sun's heat energy and the heat derived from the conbustion of wood?

4. What is the origin of natural gas?

5. How does the sun produce the power which may be realized from a waterfall?

6. Is the earth solid throughout? Explain.

7. Is the heat of the earth's interior available for producing power?

8. What causes the heating of an engine bearing? Is the heat due to friction in an engine bearing of any practical use in heating the room?

9. How does compression of a gas affect the temperature of the gas?

10. Name some uses of the heat which is always developed when an electric current flows in a conductor.

11. Explain how heat is developed by the combustion of fuels.

12. What transformation of energy occurs when coal burns?

DIVISION 4

HEAT—ITS MEASUREMENT AND TRANSFORMATIONS

75. The Amount Or Quantity Of Heat Which Any Portion Of Matter Contains is determined by: (1) *The weight of the portion of matter.* (2) *The nature of the substance.* (3) *Its condition, whether solid, liquid, or gaseous.* (4) *Its temperature.* (5) *Its pressure,* if the substance is a gas. Therefore, if the condition and characteristics, as specified in the five preceding items, are known, concerning a body, the quantity of heat which it contains can, as will be shown, be determined.

76. For Measuring Quantity Of Heat A Unit Is Necessary.—The ancient philosophers thought that heat was a fluid. Heat does resemble a subtle fluid, in that it may be "poured into" a portion of matter to make it warmer, or "drawn out" of the body to cool it. Just as the gallon is the unit for measuring quantity of water, so the British thermal unit (which is defined in the following section) is a unit by which quantity of heat may be measured. But it should be remembered that heat is by no means a fluid. It is (Sec. 32) kinetic molecular energy.

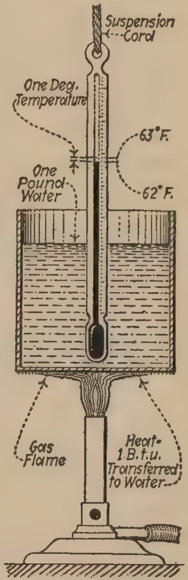


FIG. 85.—One B.t.u. = quantity of heat required to raise 1 lb of water 1° F

77. A Unit For Measuring Quantity Of Heat Is The "British Thermal Unit" (B.t.u.).—A definition, sufficiently accurate for practical purposes, is this (Fig. 85)—*A British thermal unit is the amount or quantity of heat, required to increase the temperature of 1 lb. of water, 1° F.* The preceding interpretation is the one which will be assumed in this book, unless otherwise specified.

NOTE.—TO DEFINE THE B.T.U., WITH SCIENTIFIC ACCURACY, the temperature range must be specified definitely. The usually-accepted technical definition is: *A B.t.u. is the amount of heat required to raise the temperature of 1 lb. of water from* 62° *F. to* 63° *F.* Certain authorities specify the lower temperature as 15° C. (59° F.), while others specify 39.1° F., at which temperature water has its maximum density. Another definition states that "a B.t.u. is $\frac{1}{180}$ of the total heat required to raise the temperature of 1 lb. of water from the freezing to the boiling point." Due to the fact that experiments show that the heat actually required to raise the temperature of water 1° F., varies with the temperature of the water, it is essential, in precise laboratory determinations, that the unit be defined accurately. But the technicalities introduced in the different definitions, given in this note, can be disregarded in practical engineering.

78. The Formula For Computing The Amount Of Heat Required To Change The Temperature Of Water A Specified Degree Is:

$$Q = W(T_2 - T_1) \qquad \text{(British thermal units)} \tag{22}$$

Wherein: Q = amount of heat added or subtracted, in British thermal units. W = weight of water, in pounds. T_1 and T_2 = respectively, upper and lower temperatures, in degrees Fahrenheit.

DERIVATION.—Since by definition, 1 B.t.u. will increase the temperature of 1 lb. of water 1° F., it is merely necessary, in order to determine the heat required to increase the temperature of the water any number of degrees Fahrenheit, to multiply the weight of water, under consideration, by the rise, in temperature which occurs, in degrees Fahrenheit. This operation is the one which the formula specifies.

EXAMPLE.—How much heat is required to raise the temperature of 1 gal. of water from 75 to 101° F.? SOLUTION.—A gallon of water weighs 8.3 lb. Substituting in For. (22): $Q = W(T_2 - T_1) = 8.3(101 - 75) = 216$ *B.t.u.*

79. The Small Calorie Is The Metric Unit Of Quantity Of Heat.—The *small calorie* is used almost exclusively in physical-laboratory work, the world over. The small calorie is the amount of heat required to raise the temperature of 1 gram (1 cubic centimeter) of water 1° C.

$$1 \textit{ B.t.u.} = 252 \textit{ small calories.} \tag{23}$$

$$1 \textit{ small calorie} = 0.004 \textit{ B.t.u. (approximately)} \tag{24}$$

NOTE.—THE KILOGRAM CALORIE, OR LARGE CALORIE, is one thousand times as great as the small calorie. It is used in engineering computations in countries which have adopted the metric system.

(25) 1 *B.t.u.* = 0.252 *large calorie.*

(26) 1 *large calorie* = 3.968 *B.t.u.*

NOTE.—WHERE HEAT QUANTITY IS SPECIFIED IN CALORIES, it should be designated whether the *large calorie* or the *small calorie* is implied.

EXAMPLE.—How many small calories are equivalent to 615 B.t.u.? SOLUTION.—Now, 1 B.t.u. = 252 small calories. Therefore, 615 *B.t.u.* = 615 × 252 = 154,980 *small calories.*

EXAMPLE.—How many B.t.u. are required to raise 5 kilograms of water 5° C. in temperature? SOLUTION.—It is a fact that: 5 *kilograms* = 5,000 *grams.* Hence, *heat required to raise* 5,000 *grams,* 5° *C.* = *gm.* × *deg. Cent.* = 5,000 × 5 = 25,000 *small calories.* Now, 1 *small calorie* = 0.004 *B.t.u.* Therefore, 25,000 *cal.* = 25,000 × 0.004 = 100 *B.t.u.*

80. The First Law Of Thermodynamics is: *Heat and mechanical energy can be converted one to the other and, when thus converted, a definite relationship always exists.* This follows from the statements of Secs. 25 and 26. It means that heat energy can be transformed into mechanical energy (Fig. 86) and, conversely, that mechanical energy can be converted to heat energy; it means, further, that for each unit (1 B.t.u., for example) of heat energy that is converted into mechanical energy, a certain number of mechanical-energy units (foot-pounds) will be formed, and vice versa. The original number of energy units of one kind of energy determines the number of energy units of the other kind that will result from a perfect conversion. See following sections.

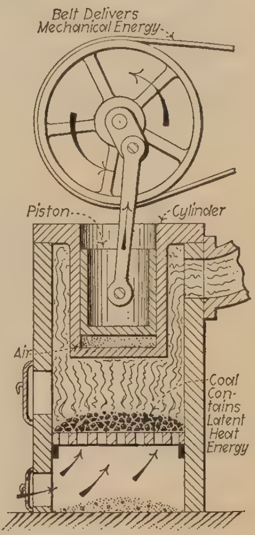

Belt Delivers Mechanical Energy
Piston
Cylinder
Air
Coal Contains Latent Heat Energy

FIG. 86.—Heating a confined gas in a hot-air engine increases the volume of the gas and thereby converts heat into mechanical energy.

81. Since "Heat And Mechanical Energy May Be Converted From One To The Other" There Must Obviously Be A Mechanical Unit Equivalent Of The British Thermal Unit.—The foot-pound (Sec. 22) is a unit of mechanical energy. The B.t.u. is a unit of heat energy. It follows, therefore, that a B.t.u. should be equivalent to a certain definite number of foot-pounds. Experiments have proven that it is.

82. The Mechanical Equivalent Of Heat, that is, *the number of foot-pounds in a B.t.u.* has been determined and verified thousands of times. The principle of the apparatus involved is explained below. All of these experiments show that for practical engineering purposes.

$$1\ \textit{B.t.u.} = 778\ \textit{ft.-lb.} \tag{27}$$

$$1\ \textit{ft.-lb.} = 0.001{,}28\ \textit{B.t.u.} \tag{28}$$

$$1\ \textit{hp.} = 42.42\ \textit{B.t.u. per min.} \tag{29}$$

$$1\ \textit{hp.} = 2{,}545\ \textit{B.t.u. per hr.} \tag{30}$$

NOTE.—PRECISE DETERMINATIONS OF THE MECHANICAL EQUIVALENT OF HEAT by the *United States Bureau of Standards* indicate that: 1 *B.t.u.* = 778.2 *ft.-lb.*, when 1 B.t.u. is taken as the heat necessary to raise the temperature of 1 lb. of water from 59 to 60° F., and = 777.5 *ft.-lb.* when the B.t.u. is measured at 62° F. A B.t.u. is often taken as equal to 778 ft.-lb., as stated above. The arrangement used for determining the mechanical equivalent of heat (Fig. 87) provides for the measuring of the heat energy imparted to a known weight of water, *H*, by the foot-pounds of work done on the water, through the action of submerged paddles, *P*, which are caused to rotate by a falling weight, *W*. See also Figs. 88 and 89 for another arrangement for determining the mechanical equivalent of heat.

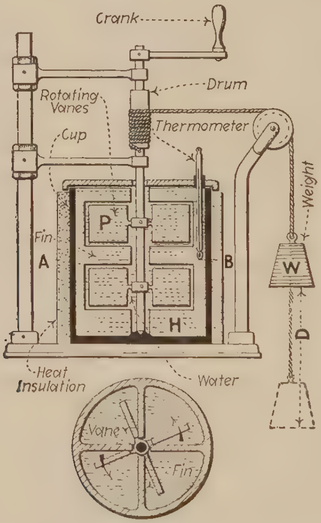


FIG. 87.—Apparatus for determining mechanical equivalent of heat.

EXPLANATION.—The foot-pounds of work done by W (Fig. 87), in falling a distance D is (neglecting friction, which can be rendered insignificant) expended solely in stirring the water H. The friction produced thereby raises the temperature of the water. This indicates that heat has been imparted to the water. By noting the rise in temperature and the weight of water, the amount of heat energy which results from the expenditure of the mechanical energy may be calculated readily.

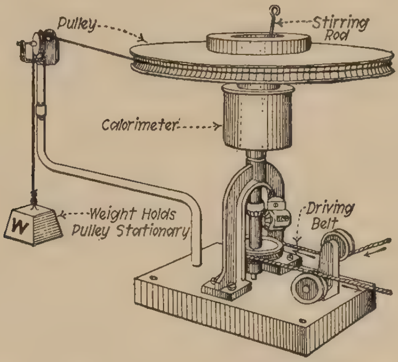


FIG. 88.—Mechanical equivalent of heat apparatus. (*Central Scientific Co.*) See succeeding illustration. The falling weight does work—expends energy—which heats the water in the container.

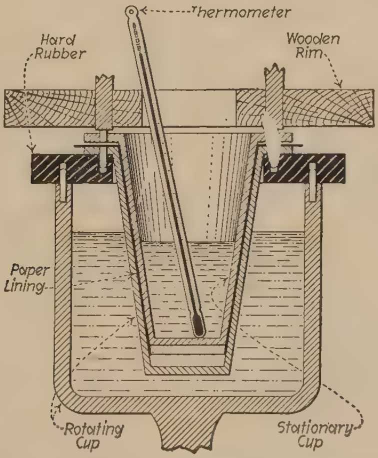


FIG. 89.—Section of friction element of mechanical equivalent apparatus. (This is a partial sectional view of the equipment shown in the preceding illustration.)

EXAMPLE.—Water weighing 125 lb. and at 60° F. is held in a container, like that of Fig. 87. It is stirred by the paddles which are actuated by a falling weight, which, when the temperature of the water has attained 63° F., has developed 291,750 ft.-lb., of work. Assuming that all exterior friction is negligible, how many foot-pounds does each B.t.u. of heat, imparted to the water, represent. Solution.—Heat absorbed by the water, For. (22) = $Q = W\ (T_2 - T_1) = 125 \times (63 - 60) = 125 \times 3 = 375$ *B.t.u.* Then the *foot-pounds expended per B.t.u.* = 291,750 ÷ 375 = 778 *ft.-lb.*, which is the mechanical equivalent of heat as specified above.

83. The Mechanical Equivalent Of Heat May Be Determined Electrically with an apparatus (Fig. 90) whereby the electrical energy is expended in a resistor which is submerged in a vessel containing a known weight of water. The watthours energy expenditure can be reduced readily to foot-pounds. (It is a fact that: 1 *watt-hour* = 2,655.4 *ft.-lb.*) Then, knowing the initial and final temperatures of the water, the mechanical equivalent of heat can be determined.

84. The Second Law Of Thermodynamics may be stated in many ways; two statements of the law are given here: (1) *Heat has never been known to flow of its own accord from a cold to a relatively hotter body.* (2) *It is impossible to obtain work by cooling any portion of matter below the temperature of the coldest of surrounding objects.* To cause heat to flow from a cold to a relatively hotter body (as it does in refrigerating machines) an expenditure of energy is required. The consequences of this law are of great importance. It will be shown by means of this law that heat can never be completely converted into mechanical energy—not even under ideal conditions. Whenever heat energy is converted into mechanical energy, some of the heat must remain in the unconverted state as heat energy. The heat which cannot be converted may be considered as an unavoidable "loss," although the heat is not actually lost.

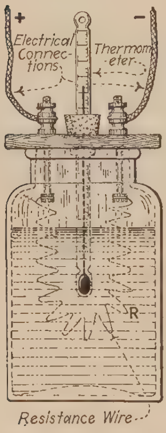


Fig. 90.—Electrical calorimeter for determining heating effect of electric current.

Example.—Much of the heat of the steam from a boiler may be unavoidably "lost" (Fig. 91) by radiation from the pipes and through the exhaust from the engines. But this "lost" heat raises the temperature of the surrounding atmosphere, and is absorbed therein.

NOTE.—THE FLOW OF HEAT IS SIMILAR TO THE FLOW OF WATER. If temperature be thought of as a sort of "head" or vertical distance, then certain heat phenomena become very clear. Thus, it is known to everyone that water will not, of its own accord, flow uphill. Statement (1) above is very similar. Likewise, it may be said that it is, in general, impossible to obtain work from a stream of water by allowing the water to flow to an elevation lower than that of the height of the lowest nearby natural stream. This is shown by Fig. 92. In *II*, Fig. 92, the centrifugal pump will be found to require more power than is gained by using Arrangement *II* instead of Arrangement *I*. This idea is similar to that of statement (2) above.

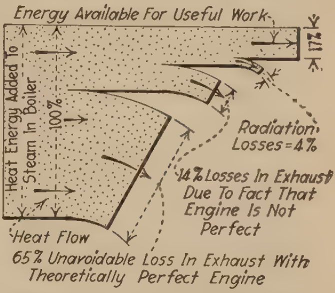
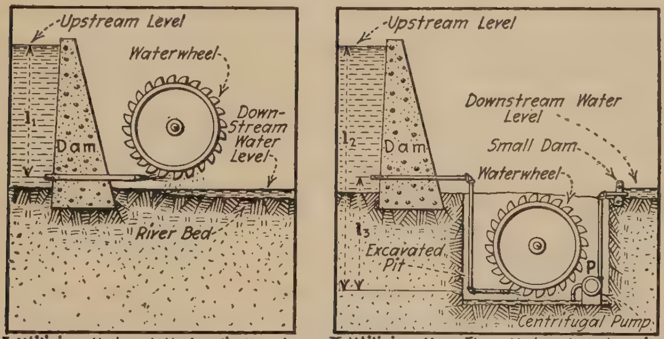

Energy Available For Useful Work
17%
Heat Energy Added To Steam In Boiler
100%
Radiation Losses = 4%
14% Losses In Exhaust Due To Fact That Engine Is Not Perfect
Heat Flow
65% Unavoidable Loss In Exhaust With Theoretically Perfect Engine

FIG. 91.—Diagram showing distribution of energy in a non-condensing steam plant (values are typical but approximate only).

NOTE.—THE SECOND LAW OF THERMODYNAMICS CONTRADICTS THE POSSIBILITY OF PERPETUAL MOTION.—If heat could be taken from the atmosphere, which contains an almost unlimited supply of heat, and could be converted into work, then it would be possible to derive mechanical energy without the expenditure of chemical energy, as from a fuel.



I-Utilizing Natural Hydraulic Head

II-Utilizing More Than Natural Hydraulic Head And Pumping Water Up To River Level

FIG. 92.—Illustrating the second law of thermodynamics. The head, l_2, in *II* is greater by the distance l_3, than that, l_1, in *I*. But nothing is gained in *II* by increasing the head by l_3 because the water has to be pumped back up again to the "elevation of the lowest nearby natural stream" so that it can flow away. In fact arrangement *II* would actually be considerably less efficient than that of *I* because of the losses in the additional piping and in the centrifugal pump *P*. This pump would have to be driven by the water wheel.

But, as stipulated by the second law—statement (2) above—it is impossible to obtain work from the atmosphere, or from anything else, by cooling it below the temperature of the coldest surrounding objects. Now, the temperature of the atmosphere is a sort of sea-level of temperature—it is the temperature to which all bodies either hotter or colder will ultimately some if left to themselves. To obtain work from a hydraulic motor or waterwheel, there must be a head of water; that is, there must be a decrease of altitude down to a lower level. Likewise, to obtain work from a heat motor, there must be a fall of temperature and this requires a source of heat at a temperature higher than atmospheric. Or, using the atmosphere as a heat source, there would be required a refrigerator, or cooling medium, at a temperature lower than that of the atmosphere. The latter alternative is impossible, for there cannot be found in nature any portion of matter which is permanently colder than the atmosphere and which can be used as a refrigerator. Hence, it is impossible to obtain work from the heat in the atmosphere.

85. The Conversion Of Heat Energy Into Mechanical Energy Can Never Be Complete.—Theoretically, it would be possible to completely convert heat energy into mechanical energy *if a substance were found whose temperature is absolute zero* (Sec. 61). But since, as stated in the preceding note, no substance can be found the temperature of which is permanently lower than that of the atmosphere, every transformation of heat energy into mechanical energy, even though the machine is frictionless, will involve a loss due to *rejected* or *degraded heat* which *cannot* be transformed into mechanical energy.

An Example Of This Degraded Heat is the heat in the exhaust of a steam engine, steam turbine, or internal-combustion engine. This degraded heat energy is comparable to the potential energy in the water which is discarded by a hydraulic motor or waterwheel—the discarded water is still about 3,950 miles from the center of the earth and therefore still contains a great amount of potential energy. But this energy cannot be utilized in a waterwheel because the waterwheel must discard its water into a nearby stream. Hence no waterwheel utilizes, or converts into useful mechanical energy, all of the potential energy in its water supply.

86. The Conversion Of Mechanical Energy Into Heat Energy Usually Is Complete.—Compare this with the opening statement of the preceding section. If a brake be applied to a turning wheel, all of the mechanical energy (which is consumed in overcoming the resistance of the brake) will be transformed into heat—which will raise the temperature of the brake, wheel and surrounding objects and air. In fact, the apparatus for determining the mechanical equivalent of heat (Figs. 87 and 88) is based on this principle. This may again, as in the preceding section, be likened to the conversion of work into potential energy when work is done in lifting water. If 1 lb. of water is raised 1 ft. from the surface of the earth, its potential energy will be increased by 1 ft.-lb. All of the work done on the water adds to its stock of potential energy.

87. The "Thermal Capacity" Or "Heat Capacity" Of A Substance Is the quantity of heat (number of heat units) that under chosen conditions, must be added to or subtracted from the substance to change its temperature one degree. In the English system, the thermal capacity is the number of British thermal units which must be imparted to or abstracted from the substance to change its temperature 1° F. The thermal capacity of a given substance need not always be the same. It depends on the state (Sec. 49) of the substance and often on many other things.

EXAMPLES.—If a gas be heated in a container of given volume, its thermal capacity will be different than if the gas is heated in a container where it can expand—as when it forces out a piston; see following Sec. 99. For solids and liquids the thermal capacity varies slightly with the temperature (Sec. 88) but the variation is so small that, in engineering work, it is generally neglected.

88. The "Specific Heat" Or "Coefficient Of Thermal Capacity" Of A Substance is its thermal capacity (Sec. 87) per unit mass. It is the number of British thermal units that must be imparted to, or abstracted from, each *pound* of the substance to change the temperature of the substance 1° F. Just as the thermal capacities of different substances depend on the conditions under which they are heated or cooled (Sec. 87), so do also the specific heats of different substances. Figs. 93 and 94 show how the specific heats of water, carbon, and iron vary with the temperature. The specific heat of a gas may, as is explained in Div. 8, have almost any value depending on the conditions under which the gas is heated or cooled.

NOTE.—THE EXACT DEFINITION OF SPECIFIC HEAT is: *The specific heat of a substance, at a given temperature and under given external conditions, is the ratio of the thermal capacity per unit mass of this substance, at* *the given temperature and under the given conditions, to the thermal capacity per unit mass of water under some chosen standard temperature and external conditions.* If the chosen temperature and pressure for water are 63.5° F. and atmospheric pressure, then the thermal capacity of the water per unit mass is 1 and the specific heat of the substance becomes numerically equal to its thermal capacity per unit mass under the given conditions. Thus, a specific-heat value is a ratio. It merely expresses how much heat is required to raise the temperature of *any* weight of the substance by 1° as compared with the heat required to raise the temperature of *the same weight of water* by 1°.

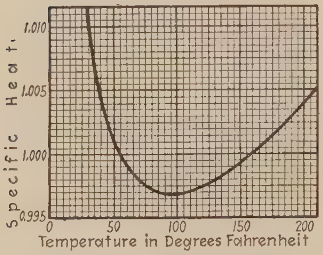


Fig. 93.—Specific heat of water at different temperatures and at saturation pressure. (Marks & Davis *Steam Tables.*)

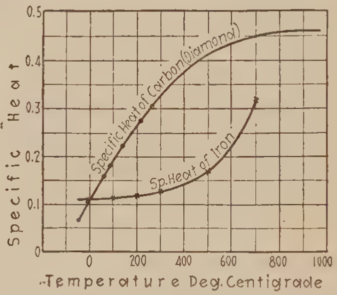


Fig. 94.—Specific heats of carbon and iron at different temperatures. (Franklin and McNutt.)

Note.—A Specific Heat Value Is Not Properly Nor Necessarily Expressible In Any Certain Unit.—There is only one specific-heat value for a given substance (See Table 90) and given conditions. This value holds regardless of what units of weight, temperature, and heat measurement are employed. In this respect, a specific heat value for a given substance is similar to a specific-gravity value.

89. Different Substances Have Different Specific Heats.—This truth may be verified by dropping two heated balls, one of copper and one of iron, each weighing 1 lb., and at the same temperature, into two vessels, both of which contain the same weight of water, at the same temperature. It will be found that the water in the vessel in which the iron ball is dropped attains the higher temperature. This shows that a pound of iron, at a given temperature, contains more heat than a pound of copper at the same temperature.

Example.—Water has (by definition of the B.t.u., Sec. 77), a specific heat of 1.0. It has the greatest specific heat or capacity for heat of any common substance. For the specific heats of various substances, see Table 90.

90. Table Showing Mean Specific Heats Of Substances Between The Temperatures Of 32 And 212° F. (These values, except those shown for gases, are all at constant atmospheric pressure.)

Substance	Specific heat	Substance	Specific heat	
SOLIDS: PURE METALS				
Aluminum	0.218	Marble	0.21	
Antimony	0.051	Paraffin wax	0.69	
Calcium	0.170	Porcelain	0.255	
Copper	0.093	Sand	0.195	
Gold	0.031	Wood, *Oak*	0.57	
Iron	0.110	Wood, *Pine*	0.67	
Lead	0.031	LIQUIDS		
Nickel	0.108	Acetic Acid	0.51	
Platinum	0.032	Alcohol	0.70	
Silver	0.056	Benzol	0.43	
Tin	0.055	Ether	0.503	
Tungsten	0.034	Gasoline	0.70	
Zinc	0.094	Glycerine	0.576	
SOLIDS: METAL ALLOYS		Kerosene	0.50	
		Machine oil	0.40	
Bell metal	0.086	Mercury	0.033	
Brass, yellow	0.088	Petroleum	0.033	
Brass, red	0.090	Sulphuric acid	0.498	
Bronze	0.104	Turpentine	0.472	
German silver	0.095	Water	1.000	
Nickel steel	0.109	MOLTEN METALS		
Solder	0.04 to .045	Lead 590°–680°	0.041	
Type metal	0.039	Tin 460°–660°	0.058	
SOLIDS: MISCELLANEOUS				
Asbestos	0.20		Constant pressure	Constant volume
Ashes	0.20			
Brick	0.22			
Carbon, coke	0.203			
Cinders	0.18			
Coal	0.314	GASES AT 62° F.		
Concrete	0.27	Air	0.238	0.169
Cork	0.485	Oxygen	0.217	0.155
Glass, *Normal*	0.199	Nitrogen	0.247	0.176
Glass, *Crown*	0.16	Hydrogen	3.420	2.440
Glass, *Flint*	0.12	Carbon monoxide (CO)	0.243	0.172
Granite	0.195	Carbon dioxide (CO_2)	0.210	0.160
Ice	0.504	Sulphur dioxide (SO_2)	0.154	0.123
India rubber	0.27 to 0.48	Ammonia (NH_3)	0.523	0.407
Limestone	0.217	*Steam (average)	0.452	0.347

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* For one condition only. See also Table 394.

91. The Formula For Determining The Specific Heat Of A Substance On The Basis Of Its Weight And Temperature Change follows from the definition of Sec. 88. It is there implied that *specific heat = B.t.u. per pound per degree temperature difference.* Note, Sec. 93 below, that this applies only when there is no change in state.

$$C = \frac{Q}{W(T_2 - T_1)} \qquad \text{(specific heat)} \tag{31}$$

Wherein: **C** = specific heat of the substance. **Q** = total heat added to the substance, in B.t.u. **W** = weight of the substance, in pounds. T_1 = temperature before **Q** is added, in degrees Fahrenheit. T_2 = temperature after **Q** is added, in degrees Fahrenheit.

EXAMPLE.—A certain mixture, weighing 10 lb., requires 7.5 B.t.u. to raise its temperature 1° F. What is the specific heat of the mixture? SOLUTION.—Substituting, For. (31): $C = Q \div [W(T_2 - T_1)] = 7.5 \div [10 \times 1] = 0.75$ = *specific heat of the mixture.*

92. The Formula For Computing The Amount Of Heat That Must Be Added To A Substance Of Known Specific Heat To Increase Its Temperature A Certain Degree Or The Heat Which Must Be Abstracted To Cool A Body A Certain Degree (when there is no change in state, Sec. 93 below) is obtained by transposing For. (31) thus:

$$Q = CW(T_2 - T_1) \qquad \text{(British thermal units)} \tag{32}$$

Wherein the symbols have the same meanings as specified above.

EXAMPLE.—The specific heat of a certain grade of coal is known to be 0.31. How many B.t.u. of heat will be required to raise the temperature of 1.5 lb. of this coal from 61 to 67° F.? SOLUTION.—Substituting, in For (32): $Q = CW(T_2 - T_1) = 0.31 \times 1.5 \times (67 - 61) = 2.79$ *B.t.u.*

93. The Above Formulas Apply Only Where There Is No Change Of State (Sec. 49). This refers to Formulas (31) and (32). If heat is added to water under atmospheric pressure, and at a temperature of 212° F., it will be found that many heat units must be added to change the temperature. Water changes into steam—changes its state—at 212° F. Much additional heat (Sec. 106) is required to effect the change. After water vaporizes into steam, its specific heat changes; see Table 90. Also, after water freezes into ice—changes from the liquid to the solid state—its specific heat is different. In fact, the doctrine just outlined, applies in general to all substances, as will be evident from a consideration of the specific heat values of Table 90.

94. To Determine The Specific Heats Of Solid Substances, The Method Of Mixtures is, ordinarily, the most practicable. A special container (Fig. 95) is employed to hold the liquid—usually water—and the solid while they are being mixed. The container is, frequently, nickel plated (Sec. 144) or lagged (Fig. 96) with heat-insulating material (Sec. 114) to minimize the ingress or egress of heat during the determination. Such a container is called a *calorimeter*. Since nearly all heat measurements are made in calorimeters, heat measurement is often termed calorimetry. The formula employed in computing the specific heat—its derivation and an explanation are given below—is:

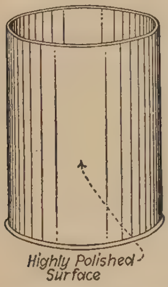

FIG. 95.—Simple calorimeter.

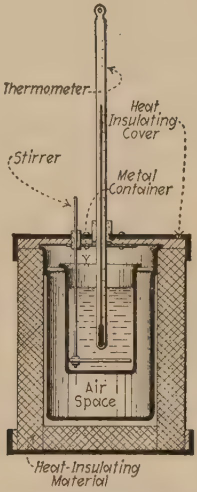

FIG. 96.—Calorimeter assembled (*Central Scientific Company*).

$$C_H = \frac{C_C W_C (T_M - T_C)}{W_H (T_H - T_M)} \quad \text{(British thermal units)} \tag{33}$$

Wherein: C_H = the specific heat of the hotter body W_C = the weight of the cooler body, in any weight unit whatsoever. C_C = the specific heat of the cooler body; if water is used for the cooler body this specific heat will be "1." T_M = the final temperature of the mixture, in any temperature unit whatsoever. T_C = the original temperature of the cooler body expressed in the same temperature unit as T_M. W_H = the weight of the hotter body, expressed in the same weight unit as W_C. T_H = the original temperature of the hotter body, expressed in the same temperature unit as T_M.

Derivation.—In the method of mixtures, the cooler body absorbs heat and the hotter body looses heat. Obviously, the amount of heat gained by the cooler body must equal the amount of heat lost by the hotter body. This must be true since the calorimeter is so constructed that no heat can enter or leave it during the determination. Also, it is an obvious fact that the originally-cooler body and the originally-hotter body must finally attain exactly the same temperature in the calorimeter, which temperature is herein designated by T_M. Now, from For. (32), the heat gained by the cooler body will be:

$$Q = C_C W_C (T_M - T_C) \qquad \text{(British thermal units)} \tag{34}$$

Also, from For. (32), the heat lost by the hotter body will be:

$$Q = C_H W_H (T_H - T_M) \qquad \text{(British thermal units)} \tag{35}$$

Since the heat gained by the cooler body, as expressed by For. (34), must equal the heat lost by the hotter body, which is expressed by For. (35), it follows that:

$$C_C W_C (T_M - T_C) = C_H W_H (T_H - T_M) \tag{36}$$

Now, assuming that it is desired to solve for the specific heat of the hotter body, by transposing For. (36) there results:

$$C_H = \frac{C_C W_C \, (T_M - T_C)}{W_H (T_H - T_M)} \qquad \text{(specific heat)} \tag{37}$$

which is the same as For. (33).

Example.—What is the specific heat of lead? The lead weighs 3 lb. The water in the calorimeter (Fig. 97) weighs 4 lb. The temperature of the lead, before immersing in the water was 210° F. The initial temperature of the water in the calorimeter was 55° F. The maximum temperature of the water-lead mixture in the calorimeter, after adding the hot lead, is 58.47° F. Solution.—Substituting in For. (33): $C_H = C_C W_C (T_M - T_C) / W_H (T_H - T_M) = [1 \times 4(58.47 - 55)] \div [3(210 - 58.47)] = 13.88 \div 454.59 = 0.031$.

Explanation.—It Is Desired (Fig. 97) To Determine The Specific Heat Of Lead. All that are necessary are: (1) *Some pure water.* (2) *Lead shot.* (3) *Two thermometers.* (4) *Calorimeter.* (5) *A method of heating the lead.* First, pour a known weight of water (say 4 lb.), which should be at about room-temperature, into the calorimeter. Determine accurately the temperature of this water (say it is 55° F.). Now pour the shot into a container, a test tube will do. Then lower the test tube and shot (say 3 lb.) into, and permit them to remain in a vessel of hot water until the shot become heated to some certain observed temperature, say 210° F.

Next, the 210° F. shot are poured from the test tube into the water in the calorimeter, which should contain a thermometer. The temperature of this water will be observed to increase considerably due to the heat flowing from the hot shot into the water. Note the maximum temperature which the water attains (say it is 58.47° F.).

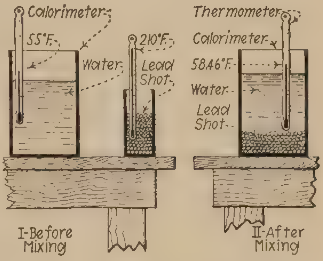

Fig. 97.—Determining specific heat of lead by the "method of mixtures."

Now, obviously, the temperature of the lead has decreased. The temperature of the water has increased. Since the weight of the water in the calorimeter and its temperature rise are known, the B.t.u. of heat imparted to it by the shot may be computed by applying For. (32). This heat in B.t.u. (imparted to the water by the shot) must be the same amount of heat as that which is given up by the lead. Then, since the temperature in degrees, the weight, and the amount of heat given by the lead to the water are known, the specific heat of the lead may be determined, readily, by using For. (32) transposed. Study the following solution, of the example above given, in which it is assumed that there are no heat losses to the air or to the calorimeter and its insulating material. This solution illustrates another slightly different method of calculating specific heat. In a practical problem, the heat-loss items would require consideration, if accurate results are essential.

Solution.—By For. (32) *the heat imparted to the water* $= \mathrm{Q} = \mathrm{C} \times \mathrm{W}(T_2 - T_1) = 1 \times 4\ (58.47 - 55) = 13.88$ *B.t.u.* Therefore, also *the heat given up by the lead* = 13.88 B.t.u. That is, *the heat lost from the lead = heat gained by the water.* Then, $\mathrm{Q} = \mathrm{C}_H \mathrm{W}_H(T_H - T_M)$ or $\mathrm{C}_H = \mathrm{Q} \div [\mathrm{W}_H(T_H - T_M)] = 13.88 \div [3(210 - 58.47)] = 0.031$, which is the specific heat of lead, as shown in Table 90.

95. The Effect Of Mixing Two Or More Different Substances Of Unequal Temperatures may be understood from a further consideration of the principles which have just been presented. Thus, if 10 lb. of water at 20° F. is mixed with 10 lb. of water at 100° F., obviously, the resulting temperature of the mixture will be: $(20 + 100) \div 2 = 60°$ F. However, if 10 lb. of water at 20° F. is mixed with 10 lb. of copper at 100° F., the temperature after mixing will not be 60° F. The resulting temperature can—if there is no change of state, Sec. 93, as a result of the mixing—be computed by using this formula:

$$(38) \quad T = \frac{\mathrm{W}_1\mathrm{C}_1T_1 + \mathrm{W}_2\mathrm{C}_2T_2 + \mathrm{W}_3\mathrm{C}_3T_3 + etc.}{\mathrm{W}_1\mathrm{C}_1 + \mathrm{W}_2\mathrm{C}_2 + \mathrm{W}_3\mathrm{C}_3 + etc.} \quad \text{(degrees)}$$

Wherein: W_1, W_2, W_3, *etc.* = respectively, the weights of the different substances of the mixture, in any weight unit whatsoever providing all are in the same unit. C_1, C_2, C_3, *etc.* = respectively, the corresponding specific heats of the different substances. T_1, T_2, T_3, *etc.* = respectively, the corresponding initial temperatures of the different substances, in any temperature unit provided all are in the same unit. T = the resulting final temperature of the mixture, in the same temperature unit as T_1, T_2, T_3, *etc.*

DERIVATION.—Temperatures as shown by thermometer scales are reckoned above an arbitrary datum or "zero." Now, by definitions: *The heat in a substance above the arbitrary zero = Weight × Specific heat × Temperature above* 0°. That is, using symbols, the heat, Q, in a substance above 0° may be expressed by:

$$Q = WCT \qquad \text{(heat)} \tag{39}$$

or by transposing For. (39), the temperature, T, of a substance of known weight, W, known specific heat, C, and to which has been added a known quantity of heat, Q, will be:

$$T = \frac{Q}{WC} = \frac{\textit{Quantity of heat above } 0^\circ}{\textit{Weight} \times \textit{Specific heat}} \qquad \text{(degrees)} \tag{40}$$

Now where several different component substances of different specific heats and different weights are "mixed" to form one "substance," it follows that:

$$Q = W_1C_1T_1 + W_2C_2T_2 + W_3C_3T_3 + \textit{etc.} \qquad \text{(heat)} \tag{41}$$

Furthermore, it also follows that for the same several different substances:

$$WC = W_1C_1 + W_2C_2 + W_3C_3 + \textit{etc.} \qquad \text{(thermal capacity)} \tag{42}$$

Hence, substituting Fors. (41) and (42) for their equivalents in For. (40), there results:

$$T = \frac{W_1C_1T_1 + W_2C_2T_2 + W_3C_3T_3 + \textit{etc.}}{W_1C_1 + W_2C_2 + W_3C_3 + \textit{etc.}} \qquad \text{(degrees)} \tag{43}$$

which is the same as For. (38).

EXAMPLE.—If 40 lb. of water at a temperature of 160° F. is mixed with 21 lb. of water at 52° F., what is the temperature of the mixture? It is assumed that no heat is gained or lost by the vessel in which the mixing occurs. SOLUTION.—The specific heat of water is "1." Now substitute in For. (38): $T = (W_1C_1T_1 + W_2C_2T_2)/(W_1C_1 + W_2C_2) = [(40 \times 1 \times 160) + (21 \times 1 \times 52)] \div [(40 \times 1) + (21 \times 1)] = (6{,}400 + 1{,}092) \div (40 + 21) = 7{,}492 \div 61 = 122.82° F.$

EXAMPLE.—A block of wrought iron which weighs 3.25 lb. is heated to a temperature of 780° F. This hot iron block is dropped into a copper pan, which weighs 2 lb. and which contains 7.8 lb. of water. Both the water and the pan are at a temperature of 80° F. What, assuming no loss or gain of heat to or from outside sources, will be the final temperature of the "mixture"? SOLUTION.—Assume the following specific heats: Copper = 0.095. Water = 1. Wrought iron = 0.114. Now substitute in For. (38): $T = (W_1C_1T_1 + W_2C_2T_2 + W_3C_3T_3)/(W_1C_1 + W_2C_2 + W_3C_3) = [(3.25 \times 0.114 \times 780) + (2 \times 0.095 \times 80) + (7.8 \times 1 \times 80)] \div [(3.25 \times 0.114) + (2 \times 0.095) + (7.8 \times 1)] = 111.0° F.$

EXAMPLE ILLUSTRATING HOW THE TEMPERATURE OF A FURNACE MAY BE DETERMINED BY APPLYING THE "METHOD OF MIXTURES."—A block of wrought iron which weighs 1 lb. is placed in a furnace and permitted to remain there until it attains the temperature of the furnace. It is then removed and placed in a copper bucket which contains exactly 2 lb. of water at a temperature of 75° F. The copper bucket weighs ½ lb. The final temperature of the mixture is 156° F. What was the temperature of the furnace? (Assume that none of the water is vaporized into steam and that there is no exterior loss or gain of heat by the bucket.) SOLUTION.—Use the values for specific heats which are given in the preceding example. Now transposing For. (38) for T_1 there results $T_1 = [T(W_1C_1 + W_2C_2 + W_3C_3) - (W_2C_2T_2 + W_3C_3T_3)]/W_1C_1$. Now, substituting the values above given in this formula: $T_1 = [156 \times (1 \times 0.114 + 0.5 \times 0.095 + 2 \times 1) - (0.5 \times 0.095 \times 75 + 2 \times 1 \times 75)] \div (1 \times 0.114) = [156 \times (0.114 + 0.048 + 2) - (3.562 + 150)] \div 0.114 = [156 \times 2.162 - 153.562] \div 0.114 = [337.272 - 153.562] \div 0.114 = 183.71 \div 0.114 = 1{,}613° F.$, which is the temperature of the iron block when it was dropped into the water, and therefore the temperature of the furnace.

96. Heat Energy, When Added To A Substance, May Be Expended In Three Ways and in only three ways. (The three different kinds of heat were already mentioned in Sec. 54, in connection with the three possible effects of heat transfer.) The heat energy may be expended in doing: (1) *Vibration work.* (2) *Disgregation work.* (3) *External work.* *All* of the heat transferred must be expended in one, two, or all three of these ways. Likewise, heat energy when abstracted from a substance may be the result of vibration work, disgregation work, or external work—any one, two, or all three. Thus, as will be shown, the vibration work, disgregation work, and external work may be "positive" or "negative," depending on whether heat energy is added or abstracted and upon the pressure conditions during the transfer of heat. In general, the work will be positive when heat energy is added and will be negative when heat energy is abstracted. These three kinds of work are further explained in following sections.

Example.—(*a*) *Imagine that a piece of ice*, the temperature of which is −60° F. (60° F. below zero) is warmed by the gradual addition of heat. The ice is assumed to be heated in a vessel which is open to the atmosphere. Its temperature will rise gradually up to 32° F. During this warming, the volume of the ice is increased but slightly. Hence, little *external work* was done by the expansion of the ice against the external atmospheric pressure; also, very little work (*disgregation work*) was done in separating the molecules which composed the ice. Therefore, nearly all of the added heat is expended as *vibration work* to increase the temperature of the ice.

(*b*) *When the temperature of the ice reaches* 32° *F.* (due to the gradual heating), a change may be noted. The temperature of the ice ceases to rise as more heat is imparted to it. It is found, however, that the ice gradually changes from the solid to the liquid state—it melts into water; the added heat is expended in *disgregation work.* During the entire melting process, the temperature of the mixture of ice and water remains at the temperature of 32° F.; no *vibration work* has been done. During this change of state, the volume of the substance has been changed; hence, *external work* has also been done. How the addition of heat changes the "state" is explained in Sec. 98.

(*c*) *After all the ice has been melted*, the further addition of heat will again increase the temperature of the substance (now water), which requires *vibration work.* The temperature will increase until it reaches 212° F. During this interval the volume will again increase but little; little *disgregation work* and little *external work* is done. Hence, nearly all of the heat imparted to the water may be said to be expended in *vibration work* in increasing the temperature of the water as in (*a*).

(*d*) *When the temperature of the water reaches* 212° *F.* (due to the continued gradual heating) another change is noted. The temperature of the water ceases to rise as more heat is imparted to it. It is found, however, that the water gradually changes from the liquid to the gaseous state—it evaporates into steam. If the enclosing vessel is large enough, the steam will be collected above the water surface and its volume will be found to rapidly increase forcing out the air which previously occupied this space. Finally, all of the water will be evaporated into steam whose temperature is 212° F. The volume of the steam will be about 1,600 times that of the water just before evaporation began. Hence, during the change from water at 212° F. to steam at 212° F., the heat which was added did two things: (1) It, by the expenditure of *disgregation work*, changed the water into steam. (2) It, by doing *external work*, drove out the air from the enclosing vessel. Hence, the heat was effective in changing the state of the substance and in doing external work but it did not change the temperature of the substance. [Compare with (*b*).]

(*e*) *After the water has all been evaporated into steam*, a further gradual addition of heat will again do *vibration work* and thereby increase the temperature of the substance (now steam). The volume of the steam will at the same time increase quite rapidly and by doing *external work* force out more air from the containing vessel. The molecules of steam are separated somewhat so that, in a sense, there is a change of state—an expenditure of *disgregation work*—but this change is not as pronounced as those in (*b*) and (*d*) above. Hence, the addition of heat to the evaporated steam is effective in (1) *Doing vibration work* in increasing its temperature. (2) *Doing disgregation work* in changing its state. (3) *Doing external work.*

(*f*) *After the steam is heated to some very-high temperature,* it will again be found that further gradual addition of heat will not increase its temperature. There is still another change of "state." Now the atoms of which the steam molecules are composed (hydrogen and oxygen atoms) will be separated. In other words, the steam will, by the expenditure of *disgregation work*, be *dissociated* into hydrogen and oxygen. Hence, the change may be called a chemical change. The temperature at which this dissociation takes place is, however, so high that it is uncommon in heat engineering. Furthermore, the study of dissociation is beyond the scope of this book and will not be further treated herein. It is mentioned here simply to show that there is change of state which even some gaseous substances may undergo when heated.

97. Vibration Work, symbol W_V, is the work (which can be measured in foot-pounds but is most conveniently measured in B.t.u.) which is done by the vibration heat (Sec. 54). It is the work which is done by added vibration heat on the molecules of a substance in increasing their kinetic energy—vibrational velocity—and, thus in increasing the temperature of the substance. Or similarly it is the work which is done by subtracted vibration heat, in decreasing temperature. Thus, when the temperature of a substance is decreased, the molecules of the substance give up a portion of their kinetic energy—hence, "negative" vibration work is done. *Vibration heat* is, therefore, also called *temperature heat*, *thermometer heat*, and *sensible heat* (because it is the heat which affects the sense of touch). A formula for vibration work may be written thus:

$$W_V = 778\mathbf{Q}_V \qquad \text{(foot-pounds)} \tag{44}$$

Wherein: W_V = the vibration work, in foot-pounds $\mathbf{Q}_V$ = the vibration heat, in B.t.u. 778 = the mechanical equivalent of heat (Sec. 82). W_V and $\mathbf{Q}_V$ are both positive when the temperature of a substance is raised and are both negative when the temperature is decreased.

EXAMPLE.—A gas is confined in a closed vessel (Fig. 98) which is protected (insulated) so that no heat can pass through the walls of the vessel.

A wire is led into the vessel and an electric current is passed through the wire. A transformation of electric energy into heat energy takes place and 50 B.t.u. are given to the gas. If the vessel does not permit the gas to expand, how much vibration work is done? SOLUTION.—Since the gas cannot expand, the heat energy cannot do disgregation work nor external work. Hence, the entire 50 B.t.u. is expended as vibration work. By For. (44): *the vibration work* = $W_V = 778Q_V = 778 \times 50 =$ 38,900 *ft.-lb.*

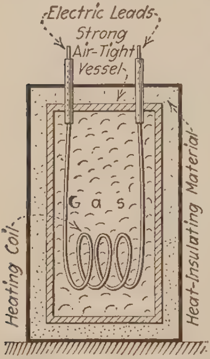

FIG. 98.—A gas being heated in a closed vessel where it cannot expand. Only vibration work is done.

EXAMPLE.—As a piece of iron is permitted to cool from 600° F. to 80° F., it is found that 250 B.t.u. are given up by the iron. How much vibration work is done? SOLUTION.—Since the temperature has been reduced, Q_V and W_V are both negative. Hence, $Q_V = -250$ B.t.u. and, by For. (44): $W_V = 778\,Q_V = 778 \times (-250) = -194{,}500$ *ft.-lb.*

NOTE.—VIBRATION WORK OR VIBRATION HEAT CAN BE DIRECTLY MEASURED only when the substance which is heated or cooled is so confined that it cannot expand or contract, as in the preceding example. With most solids and liquids, however, the expansion or contraction due to heating or cooling is, in any case, so small that only a negligible error results by assuming that all heat added or abstracted is effective as vibration heat. Hence, for solids and liquids when no change of state occurs, it is practically true that *heat added = vibration heat.* For methods of accurately determining vibration heat, see Sec. 102.

98. Disgregation Work, symbol W_D, is the work which is done by the disgregation heat (Sec. 54). It is the work which is done by added heat on the molecules of a substance in overcoming their mutual attractive forces—in increasing their potential energy by separating them—and, thus, in changing the state (Sec. 49) of the substance; this is called "positive" disgregation work. When heat is given up by a substance during a change of state, this heat is always the result of the work done by the molecules of the substance in drawing each other closer together—in doing "negative" disgregation work. A formula for disgregation work follows:

$$W_D = 778Q_D \qquad \text{(foot-pounds)} \tag{45}$$

Wherein: W_D = the disgregation work, in foot-pounds. Q_D = the disgregation heat, in B.t.u. 778 = the mechanical equivalent of heat (Sec. 82). W_D and Q_D are both positive when the state is changed from solid to liquid or liquid to gaseous. They are both negative when the state is changed from liquid to solid or gaseous to liquid.

EXAMPLE.—Assume that there was a liquid which did not expand nor contract in freezing. (Actually, all liquids do either one or the other.) Imagine further that it takes 100 B.t.u. to melt 1 lb. of this substance from the solid to the liquid state (Fig. 99). How much disgregation work is done in melting 1 lb. of this substance? SOLUTION.—Since the temperature of a substance does not change during the melting, no vibration work is done. Also, since the substance does not expand or contract, no external work is done. Hence, the entire 100 B.t.u. is effective in doing disgregation work. By For. (45): the *disgregation work* $= W_D = 778Q_D = 778 \times 100 = 77{,}800$ *ft.-lb.*

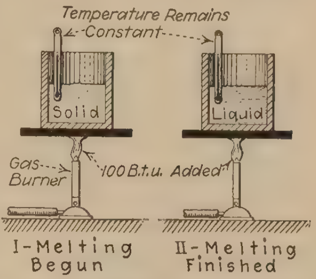

FIG. 99.—Melting 1 lb. of a substance.

EXAMPLE.—How much disgregation work is done in freezing 1 lb. of the substance of the preceding example? SOLUTION.—During freezing, Q_D and W_D are both negative. Hence, $Q_D = -100$ B.t.u., and by For. (45): $W_D = 778Q_D = 778 \times (-100) = -77{,}800$ *ft.-lb.*

NOTE.—THE DISGREGATION WORK OR DISGREGATION HEAT CAN BE MEASURED DIRECTLY only if the heated substance does not expand or contract during a change of state. In practically all cases, the disgregation work or disgregation heat is not measured directly but is computed, as will be explained, from other heat measurements.

99. External Work, symbol W_E, is the work (usually measured most conveniently in foot-pounds) which is done by the external-work heat (Sec. 54). It is the work done by the substance in expanding (Fig. 86) against restricting forces; if a body is heated in the atmosphere then the restricting forces are those which are imposed on the body by the atmospheric pressure—the body must *push away* the atmosphere. It thus does "positive" external work. If, however, during a heat transfer the volume of the body is decreased, then the external forces help to heat the body and "negative" external work is done. A formula for external work follows:

(46) $$W_E = 778Q_E \qquad \text{(foot-pounds)}$$

Wherein: W_E = the external work done, in foot-pounds.

Q_E = the external-work heat, in B.t.u. 778 = the mechanical equivalent of heat (Sec. 82). W_E and Q_E are both positive when the volume of the substance is increased; they are both negative when the volume is decreased.

Example.—Assume that a cylinder (Fig. 100) contains 1 cu. ft. of gas at a certain temperature and pressure and that the cylinder is fitted with a piston. Assume, further, that heat is supplied to the gas and the piston is permitted to move out of the cylinder at such a rate that the temperature of the gas does not change. It may here be assumed (it is proved in Sec. 258) that for a gas the disgregation work is zero. If 10 B.t.u. are imparted to the gas, how much external work does the gas do in pushing out the piston? Solution.—Since the temperature remains constant, no vibration work is done and since, as stated in the example, no disgregation work is done, all of the imparted heat must be external work heat. Hence, by For. (46): *the external work* $= W_E = 778Q_E = 778 \times 10 = 7{,}780$ *ft.-lb.*

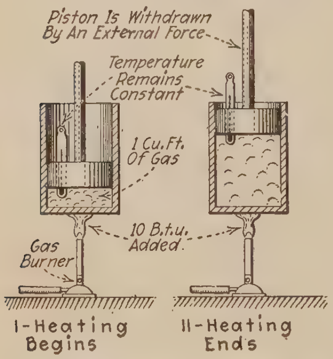

Fig. 100.—Heating a gas and maintaining a constant temperature.

Note.—External Work Is (As Further Explained In Following Sec. 263) Usually Determined From The Pressure-volume Relations During The Addition Of Heat.—If the body is subjected to a constant pressure during the heating, then (see Sec. 263 for the derivation of this formula):

(47) *External work = pressure × change in volume*

Or, expressing the same thing with symbols:

(48) $$W_E = P \times (V_2 - V_1) \qquad \text{(ft.-lb.)}$$

Wherein: W_E = the external work, in foot-pounds. P = pressure, in pounds per *square foot.* V_2 and V_1 = the final and initial volumes, respectively, of the body, in cubic feet.

If, during the heating, the pressure is not constant, then

(49) *External work = average pressure × change in volume* (ft.-lb.)

Or, the external work may be found directly from a pressure-volume diagram as explained in Sec. 262.

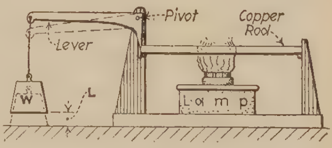

Fig. 101.—An expanding rod may do work.

Example.—The weight W (Fig. 101) weighs 10 lb. The distance, L, through which the weight has been lifted by the expansion of the copper rod, is 0.02 in. Therefore, *the work done—the energy expended—by the external heat which has manifested itself in expanding the rod* = 10 × 0.02 = 0.2 *in.-lb.*

100. If The Quantity Of Heat Which Is Transformed Into Mechanical Energy By The Expansion Of A Solid Or Liquid Were Restrained From Such Transformation, the heat would then expend its energy solely in raising the temperature. Thus it would manifest itself solely as vibration or sensible heat—instead of as external-work heat as in Fig. 101.

EXPLANATION.—Imagine an iron rod (Fig. 102) to be encased in a massive steel die, and to be heated by an electric current. The rod would tend to expand. But expansion would be prevented, in all directions, by the steel die. Hence, no external (mechanical) work could or would be done. No external-work heat could be expended. But the heat which would be transformed into mechanical work, if the rod were free to expand, would, nevertheless, manifest itself as vibration work in raising the temperature of the constrained rod. Hence, the temperature of this embedded rod would be higher than it would be if the rod were free to expand.

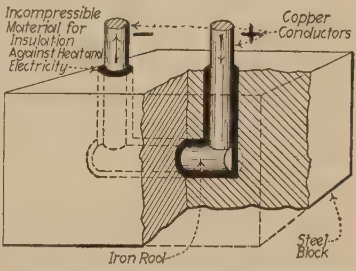
Incompressible Material for Insulation Against Heat and Electricity
−
+
Copper Conductors
Iron Rod
Steel Block

FIG. 102.—Imaginary construction of steel dies for preventing expansion of iron rod.

101. The Fundamental Heat Transfer Equation is merely a formula expressing the facts of Sec. 54. It may be written:

$$Q = Q_V + Q_D + Q_E \qquad \text{(British thermal units)} \tag{50}$$

Wherein: Q = the total heat transfer, in British thermal units.
Q_V = change in vibration heat, in British thermal units.
Q_D = change in disgregation heat, in British thermal units.
Q_E = external-work heat, in British thermal units.

If the heat effects are to be expressed in foot-pounds it follows that, since 1 *B.t.u.* = 778 *ft.-lb.* (Sec. 82), the formula will become:

$$Q = \frac{1}{778}(W_V + W_D + W_E) \qquad \text{(British thermal units)} \tag{51}$$

EXAMPLE.—A certain weight of a certain liquid substance is changed, by heating, into a vapor, at an increased temperature. To effect the change it is found that: 140 B.t.u. is expended in the external work which is done by the substance, during the process, due to the increased volume of the substance; 360 B.t.u. is expended in raising the temperature of the substance; 1,800 B.t.u. is expended in changing the state of the substance from a liquid to a gas. What total amount of heat must be transferred to the substance to effect the change? Solution.—Substituting in For. (50): $Q = Q_V + Q_D + Q_E = 360 + 1{,}800 + 140 =$ 2,300 *B.t.u. = Total heat transferred.*

Example.—It is found, by experiment, to require 1,150.4 B.t.u. to raise the temperature of 1 lb. of water from 32° F. to 212° F. and evaporate it into steam when all of the heating is done in an open vessel (atmospheric pressure). The final volume of the evaporated steam is 26.79 cu. ft. The initial volume of the water at 32° F. was approximately 0.016 cu. ft. What is the vibration heat, disgregation heat, and external-work heat? Solution.—By definition of the British thermal unit, 180 B.t.u. are required to raise the temperature from 32° F. to 212° F. By the example under Sec. 96, this may be taken as *vibration heat.* By For. (48): $W_E = P \times (V_2 - V_1) = (14.7 \times 144) \times (26.79 - 0.016) = 56{,}650$ *ft.-lb.* Now, by For. (46), transposed: *the external-work heat* $= Q_E = W_E/778 = 56{,}650 \div 778 = 72.8$ *B.t.u.* Also, by transposing For. (50): $Q_D = Q - (Q_V + Q_E) = 1{,}150.5 - (180 + 72.8) = 897.6$ *B.t.u. = disgregation heat.*

102. How The Heat Energy Does Work When A Solid Body Is Heated.—A solid body expands but little; the disgregation and external works are therefore small. When the vibration work is being considered, the disgregation work and the external work may ordinarily be neglected. When a solid body is heated, as for example a piece of iron, it is therefore, generally assumed that all of the heat is used in raising the temperature. Or, when a solid is heated:

(52) $Q = Q_V$ (very nearly) (British thermal units)

103. How The Heat Energy Does Work When A Solid Is Melted To The Liquid State.—During the melting of a solid body there is no change in its temperature; hence, no vibration work is done during the melting. Furthermore, when a body melts there is usually only a very small change in volume although some bodies expand and others contract as they melt. Hence, very little external work is usually done by the body in melting. Nearly all of the added heat is used in doing disgregation work—in overcoming the mutual attractive forces between the molecules and giving them the freedom which they have in the liquid state. Therefore, if the small amount of external work is neglected, all of the added heat (the latent heat of melting, Sec. 106) is effective in doing disgregation work; or, expressed as a formula:

(53) $Q = Q_D$ (very nearly) (British thermal units)

NOTE.—WHEN A LIQUID IS HEATED, the conditions are almost the same as when a solid is heated—expansion is very small, usually, and the disgregation and external works may ordinarily be neglected when the vibration work is being considered. Hence, For. (52) applies equally well to the heating of solids and liquids.

104. How The Heat Energy Does Work When A Liquid Is Vaporized.—As there is no change in temperature while a liquid is being vaporized, no vibration work is done. Now during vaporization the volume of the substance is increased many fold; therefore a considerable quantity of external work is done. However, by far the greater fraction of the latent heat of vaporization is used in doing disgregation work—in separating the molecules against their mutual attractive forces. During vaporization, therefore,

(54) $Q = Q_D + Q_E$ (British thermal units)

105. How The Heat Energy Does Work When A Gas Is Heated.—In a gas the molecules are so far apart in comparison to their own size that the attraction of one for the other is so small that it is inappreciable. Hence, practically no work is necessary to separate them farther. Therefore the disgregation work is zero and the formula becomes:

(55) $Q = Q_V + Q_E$ (British thermal units)

NOTE.—THE RELATIVE MAGNITUDES OF THE VIBRATION AND EXTERNAL-WORK HEATS DEPENDS ON the conditions under which the gas is heated, this is further explained in Div. 8. Suppose that the air in a cylinder is being heated (Fig. 100). The piston may be held in one position during the heating; then no external work will be done and Q_E will be zero (because the air cannot expand and do external work) and all of the heat must then go toward raising the temperature. Or, the piston may be raised by an external force at such a rate that the temperature will decrease, due to expansion, just as fast as it tends to rise due to the heating; under such conditions the temperature will remain constant ($Q_V = 0$) and all of the heat will be expended in doing external work.

106. Latent Heat is the heat energy which is required to produce changes in the physical state (Sec. 49) of a substance—to change it from solid to liquid, from liquid to gas, or the reverse of either. Thus, the change of physical state may be either a melting, freezing, vaporization (evaporation), or condensation. During melting and vaporization, heat must be supplied to the substance; during freezing and condensation heat must be abstracted from it. Furthermore, the amount of heat which must be supplied during the melting of a given weight of a substance is the same as that which must be abstracted while it freezes under the same conditions. The amount of latent heat required for melting or freezing is called the *latent heat of melting* or the *latent heat of fusion.* Likewise, during the vaporization of a certain weight of a substance the same amount of heat must be supplied as must be abstracted from it in condensing it. The amount of heat which must be transferred to or from a substance during its vaporization or condensation is called the *latent heat of vaporization* or the *latent heat of evaporation.*

NOTE.—THE LATENT HEAT IS THE SUM OF THE DISGREGATION AND EXTERNAL-WORK HEATS.—This follows from the fact that, during a change of state (under constant pressure), the temperature of a substance does not change. Hence, no vibration heat is necessary to effect the change and

$$Q_L = Q_D + Q_E \qquad \text{(British thermal units)} \tag{56}$$

Wherein: Q_L = the latent heat of the substance, in British thermal units. Q_D = the disgregation heat during a constant-pressure change of state, in British thermal units. Q_E = the external-work heat during the constant-pressure change of state, in British thermal units.

EXPLANATION.—Suppose a solid substance, as an ingot of lead, is heated until its temperature rises exactly to the melting point. The heat absorbed by the substance up to this point increases the motion of the molecules and is called (Sec. 54) vibration or sensible heat.

Now, if more heat be added to the ingot, it will instantly begin to melt. But its temperature will not rise. The heat energy which is now absorbed by the ingot is expended entirely in the work of melting—in transforming the molecular structure from the solid to the liquid state. It is disgregation heat. None of the heat is available for raising the temperature while the work of melting is going on—it is all used in separating the molecules. Hence the temperature will continue constant until the ingot is wholly melted. But at the exact instant when the melting is complete, the temperature of the molten lead will, if the heating still continues, begin to rise. The heat which was absorbed by the lead while its temperature remained stationary is its latent heat of melting. The latent heat of melting is further explained in Sec. 289 and the latent heat of vaporization in Sec. 322.

EXAMPLE.—What is the latent heat of vaporization of 1 lb. of water at atmospheric pressure? SOLUTION.—By the example under Sec. 101, $Q_D = 897.6$ B.t.u. and $Q_E = 72.8$ B.t.u. Hence, by For. (56): *the latent heat* $= Q_L = Q_D + Q_E = 897.6 + 72.8 = 970.4$ *B.t.u.*

NOTE.—LATENT HEAT MAY EXIST WITHIN A HEATED SUBSTANCE, EVEN WHEN THERE IS NO OUTWARD MANIFESTATION OF A PHYSICAL CHANGE in the substance. The latent heat present in such cases will not, however, manifest itself until a change in state occurs. Thus, water at ordinary atmospheric temperatures contains its latent heat of melting but this latent heat does not manifest itself (show its presence) until the water is cooled to the freezing point and begins to solidify or freeze.

107. "Internal Heat" Or "Intrinsic Heat" is the heat energy which is expended in doing work on the molecules both in increasing their vibrational velocity—kinetic heat energy—and in separating them against their forces of mutual attraction—increasing their potential heat energy (Sec. 52). It is the heat inside the substance. It does not include the heat energy which is expended in separating the molecules against external forces—in doing external work. Hence, during any heat transfer to or from a substance, the change in internal heat:

(57) $$Q_I = Q_V + Q_D \qquad \text{(British thermal units)}$$

(58) $$Q = Q_I + Q_E \qquad \text{(British thermal units)}$$

Wherein: Q_I = the change in internal heat, in British thermal units. Q_V = the change in vibration heat, in British thermal units. Q_D = the change in disgregation heat, in British thermal units. Q = the total heat transfer, in British thermal units. Q_E = the change in external-work heat, in British thermal units.

EXAMPLE.—How much internal heat is expended in changing 1 lb. of water from the liquid state at 32° F. to the steam state at 212° F.? SOLUTION.—By the example under Sec. 101, $Q_V = 180$ B.t.u. and $Q_D = 897.6$ B.t.u. Hence, by For. (57): the change in *internal heat* $= Q_I = Q_V + Q_D = 180 + 897.6 = 1{,}077.6$ *B.t.u.*

108. The Total Heat Of A Substance, or as it is often termed, the *total associated heat*, is, strictly speaking, the total heat energy, in the substance above the absolute zero of temperature. Actually, in practice, "total heat" is, unless otherwise specified, taken to mean the *total heat in the substance above some arbitrarily-chosen convenient reference temperature.*

NOTE.—With present means for making heat determinations it is impossible to definitely compute the total-heat contents of substances from absolute zero. Hence, it is necessary to regard some convenient degree of temperature and state as the "zero," datum point or basis for heat computations. In dealing with water and steam, the heat energy of water (in liquid form) at 32° F. is generally taken as the arbitrary zero of heat energy (see also Sec. 365). This procedure works no hardship since we are usually, in practice, interested in the amount of heat which is transferred to or from a substance, rather than in the total amount of heat which it contains above absolute zero.

Example.—What is the total heat of 1 lb. of water at 100° F? at 212° F.? Of 1 lb. of steam at 212° F.? Solution.—By For. (32), for water heated from 32° F. (the datum point) to 100° F., the *total heat* = $Q = CW(T_2 - T_1) = 1 \times 1 \times (100 - 32) = 68$ *B.t.u.* Likewise, for water at 212° F., the *total heat* = $1 \times 1 \times (212 - 32) = 180$ *B.t.u.* As given in the example under Sec. 101, for steam at 212° F., the *total heat* = 1,150.4 *B.t.u.*

QUESTIONS ON DIVISION 4

1. What properties of a substance determine the amount of heat energy that the substance contains?

2. What was the ancient philosophers' theory of the nature of heat?

3. What is the unit that is used in English-speaking countries for measuring quantities of heat? Give its definition.

4. Give the formula for computing the quantity of heat necessary for raising the temperature of water by a specified amount.

5. What is a small calorie? A large calorie? How are they related in size to the British thermal unit?

6. State the first law of thermodynamics. Is a British thermal unit the equivalent of any certain number of foot-pounds? If so, what is the number and what is it called?

7. Draw a sketch of the apparatus and explain how the mechanical equivalent of the British thermal unit is determined. Do the same for an electrical method.

8. State the second law of thermodynamics. What is the most important consequence of this law?

9. Can you give a hydraulic interpretation of the second law?

10. Can the conversion of heat energy into mechanical energy ever be complete? Explain fully and give a hydraulic analogy.

11. Is the conversion of mechanical energy into heat energy ever complete? Give an example and a hydraulic analogy.

12. What is meant by the *thermal capacity* of a substance? Is it always the same for a given substance? Give examples.

13. What is meant by the *specific heat* of a substance? How does it differ from thermal capacity? What is another name for the specific heat?

14. Have all substances the same specific heat? Explain as fully as you can and give some numerical values.

15. How can the specific heat of a substance be determined? Give the formula.

16. How would you determine how much heat must be added to a substance of known specific heat in order to raise its temperature a given amount? Give the formula.

17. Draw a sketch and describe the method of finding the specific heat of a substance by the method of mixtures.

18. In what three ways may heat energy, when added to a substance, be expended? Explain the effects of the heat energy that is added in raising the temperature of ice from below the freezing temperature to a very high temperature

19. What is meant by *vibration work?* What is the heat called that is effective in doing vibration work? Give an example of vibration work and give the formula. When and how is it measured directly?

20. What is meant by *disgregation work?* The heat which does disgregation work is how termed? Give an example of heat doing disgregation work. Give the formula. How is disgregation work measured?

21. What is meant by *external work?* The heat which does external work is how termed? Give the formula for external work. How is it generally measured? Give an example of heat doing external work.

22. State the fundamental heat-transfer equation. Upon what is it based? Give an example of its application.

23. How does heat energy do work when a solid body is heated? Explain.

24. How does heat energy do work when a solid is melted? Explain.

25. How does heat energy do work when a liquid is heated? Explain.

26. How does heat energy do work when a liquid is vaporized? Explain.

27. How does heat energy do work when a gas is heated? Explain. What are the relative magnitudes of the two kinds of work?

28. What is the meaning of the term *latent heat? Latent heat of melting? Of fusion? Of vaporization?* What two kinds of work are done by the latent heat?

29. What is the meaning of *internal heat?* What is another name for it? What two kinds of work are done by the internal heat?

30. What is meant by the *total heat* of a substance? Why is the total heat not usually used in engineering calculations? What is used instead?

PROBLEMS ON DIVISION 4

1. A bucket containing water is placed over a fire for heating. The temperature of the water is 55° F. Its weight is 35 lb. How much heat must be added to it to raise its temperature to the boiling point which is 212° F.?

2. What would be the temperature of 8 lb. of water which had an original temperature of 60° F., after 265 B.t.u. of heat has been added to it?

3. A boiler in a heating system is known to be 50 per cent efficient. The boiler is refilled with water at a temperature of 65° F. After burning the coal which liberates 50,000 B.t.u., the water has a temperature of 210° F. What is the weight of the water in the boiler?

4. After a certain time, the temperature of 15 liters of water, contained in a closed vessel, is found to be decreased 35° C. How many large calories of heat have been lost? How many B.t.u.? (A liter of water weighs one kilogram.)

5. In a certain power plant, it is found by test that an engine is delivering, as available work, 12 per cent. of the heat in the coal which is burned If 17 lb of coal are burned in one hour, what is the amount of energy delivered by the engine per hour? What horsepower is the engine delivering? (Assume that the coal contains 14,000 B.t.u. per lb)

6. In a specific-heat determination, 8.75 B.t.u. are added to 4.5 lb. of nickel. It is found that the nickel temperature increases from 65 to 83° F. What is the specific heat of the nickel?

7. A soft-steel plate which weighs 75 lb. is heated from 80 to 1500° F. Assuming that the mean specific heat of the steel is 0.115, how many B.t.u. are necessary to effect this increase in temperature?

8. Assuming that the specific heat of cast iron is 0.119, how many foot-pounds of energy are required to heat a 125-lb. iron casting from 40 to 180° F.?

9. In a certain boiler furnace, it is known that for each pound of coal burned, 30 lb. of air are supplied. This air must be heated from 65° F., and passes up the stack at a temperature of 565° F. Assuming that the specific heat of air for this temperature range is 0.24, calculate the B.t.u. necessary to heat the air for each pound of coal which is burned.

10. A 6-lb. iron casting has been heated in a furnace to a temperature of 2,300° F. It is dropped into a bucket which contains 5 gal. of water at 50° F. What will be the temperature of the water in the bucket? (Assume that the specific heat of the iron is 0.119 and that 1 gal of water weighs 8 3 lb.)

11. If 16 lb. of water at 40° F. is mixed with 10 lb. of water at 110° F., what will be the temperature of the resulting mixture?

12. A 12-lb. iron ball is heated to a temperature of 212° F. It is then dropped into 8 lb. of water at 35° F. The water temperature rises to 60° F. Compute the specific heat of the iron.

13. In Prob. 1, how much vibration work, in foot-pounds, is done?

14. If it takes 10.5 B.t.u. to melt 1 lb. of lead at its melting point of 626° F., how much disgregation work, in foot-pounds, is done on each pound of lead during the melting process?

15. Water, when under a pressure of 100 lb. per sq. in. abs., boils at 327.8° F. and, at that temperature, 1 lb. occupies a volume of 0.0177 cu. ft. When evaporated into steam at the same pressure and temperature, it occupies 4.429 cu. ft. How much external work is done in the vaporization process?

16. If, when water is evaporated under a pressure of 100 lb. per sq. in. abs. (as in Prob 15), 806.6 B.t.u. of disgregation heat are required, what is the latent heat of vaporization?

17. How much vibration heat is required to raise the temperature of 1 lb. of water from 32° F. to 327.8° F. if the specific heat of the water is 1?

18. Using the results of preceding problems, compute how much more internal energy there is in 1 lb. of steam at 100 lb. per sq. in. abs. than in 1 lb. of water at 32° F.

19. Using the results of preceding problems, compute the total heat of 1 lb. of steam at 100 lb. per sq. in. abs.

DIVISION 5

TRANSFER OF HEAT

109. Heat May Be Transferred.—If one end of a copper wire is heated, some of the heat will travel through the wire. Shortly the other end will be hot. Heated air, from the furnace in the basement of a dwelling, flows (Sec. 137) through ducts and registers into the rooms above and produces an agreeable warmth on wintry days. In cold weather the house cat curls up in front of the open fireplace in order to feel the heat which emanates from the fire.

110. Heat Is Transferred In Three Different Ways.—(1) *By conduction.* (2) *By convection.* (3) *By radiation.* Heat transfer from one body to another may occur simultaneously by one, two, or all three of these methods.

111. Heat Conduction Is Transfer Of Heat Through The Molecules Of A Substance.—Heat has been shown (Sec. 52) to be a vibratory motion of the molecules. When heat is added to any part of a body, as to one end of a copper bar, the molecules in that part vibrate more rapidly. This causes them to strike violently against the molecules in the cooler part immediately adjacent. The rapidity of the vibration among the molecules in this part is thereby also increased, and the part becomes heated. These molecules, in turn, strike violently against the molecules in the cooler part next farther away from where the heat is added initially. Thus, by successively transmitting the increased speed of vibration, the molecules conduct the heat to remote parts of the body, as to the opposite end of the copper bar.

NOTE.—CONDUCTION OF HEAT OCCURS MORE OR LESS IN ALL SUBSTANCES.—In no case, however, will conduction cause that part of a body (*A*, Fig. 103) which is farthest from the source of heat, *H*, to acquire as high a temperature as the part, *B*, which receives the heat directly. In fact (Sec. 55) there must be a temperature difference—or thermal pressure—between one point and another point, to which heat is conducted, to effect the conduction.

112. There Are Two Modes Or Forms Of Conduction.—(1) *Internal conduction,* whereby heat is transmitted from molecule to molecule within a body. (2) *External conduction,* whereby heat is transmitted from the molecules of one body to the molecules of another body, when the two bodies are in contact.

Examples.—When the entwined ends of the metal rods (*B*, Fig. 103) are heated by the flame, *H*, the free ends *A* and *A* of the rods, due to internal conduction, likewise become heated. As the metal rods (Fig. 103) become heated, some of the heat is absorbed, due to external conduction, by the bits of wax which bond the lead balls to the rods. This causes the wax to melt, thus releasing the lead balls.

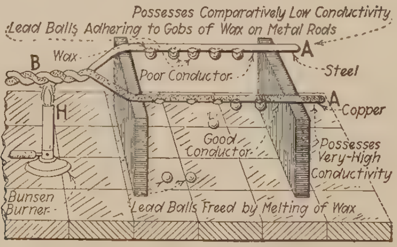
Possesses Comparatively Low Conductivity
Lead Balls Adhering to Gobs of Wax on Metal Rods
A
B
Wax
Steel
Poor Conductor
A
Copper
H
Good Conductor
Possesses Very High Conductivity
Bunsen Burner
Lead Balls Freed by Melting of Wax

Fig. 103.—The copper wire, which is a good conductor, transmits the heat more rapidly than does the steel wire.

The iron boiler tube (Fig. 104) absorbs heat from the hot gases. The heat flows, due to internal conduction, from the outer to the inner surface of the tube. It passes thence, due to external conduction, to the water which is in contact with the tube.

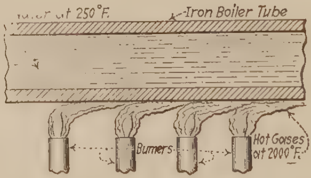

Fig. 104.—Heat conducted through the boiler tube from the hot gases to the water.

113. The Factors Which Determine The Total Transfer Of Heat By Conduction through a substance are these: (1) *The nature of the substance.* (2) *Its cross-sectional area.* (3) *The thermal pressure or temperature difference.* (4) *The length of time during which the flow occurs.* (5) *The length of the heat* *path through the substance.* Each of these factors is discussed further in succeeding sections.

114. The Nature Of A Substance Affects Its Ability To Conduct Heat.—That is, the molecules of some substances transmit the heat-energy motion, from one to another, more effectively than do the molecules of certain other substances.

Examples.—Metals are good heat conductors. Liquids (Fig. 105) are poor conductors. Air (Figs. 106 and 107) and other gases are very poor conductors. A perfect vacuum would not conduct at all because there would be no molecules in it to transmit the heat-energy motion. Some solids, such as wood and cork are poor conductors. Wooden *heat insulators* (Fig. 108) are sometimes interposed in metallic tea-pot handles to prevent the hand-hold from becoming unduly heated. Cork linings and dead-air spaces are arranged in cold-storage-room walls (see Sec. 619) to minimize the loss of heat through them.

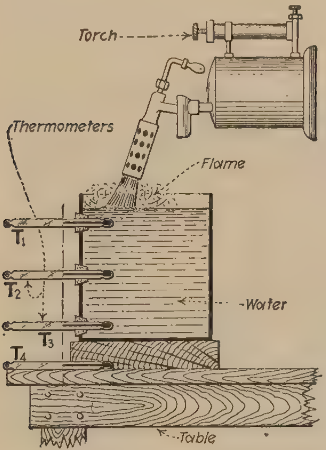

Fig. 105.

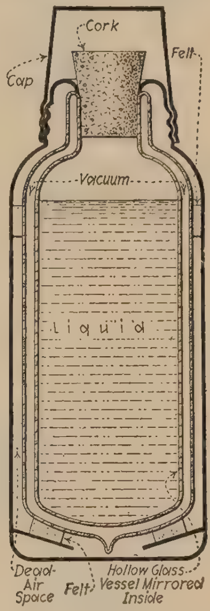

Fig. 106.

Fig. 105.—Showing that water is a poor conductor of heat. (Although the water film at the surface is boiling, all four thermometers T_1, T_2, T_3 and T_4 read practically the same temperature.)

Fig. 106.—Sectional elevation of typical "thermos" flask.

Note.—Air Is An Important Heat Insulating Material.—Any material or structure, which is composed largely of pockets of non-circulating air, provides good heat insulation. Hence, feathers, fur, felt, cork, magnesia and cellular asbestos are all good heat insulators. Like-

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wise a blanket of freshly fallen snow protects both the vegetation and the ground upon which it falls from freezing.

Note.—The Fireless Cooker (Fig. 109) provides a good example of the utilization of the poor heat-conducting properties of certain materials.

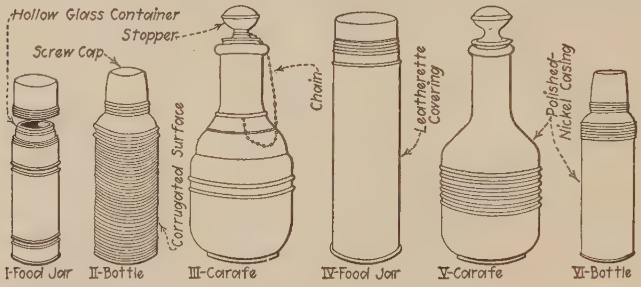
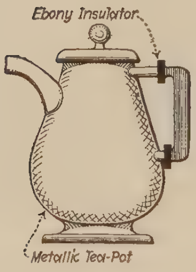


Fig. 107.—Some thermos bottles and containers. (See preceding illustration. The dead air space is a very poor heat conductor. The vacuum chamber is almost opaque to heat flow. The mirrored surfaces minimize heat radiation.)



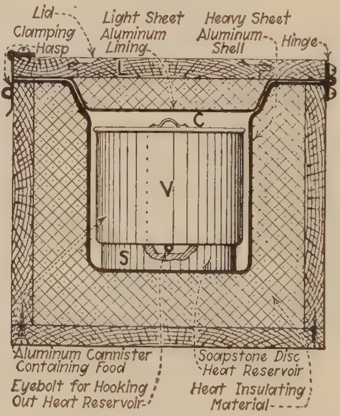

Lid
Clamping Hasp
Light Sheet Aluminum Lining
Heavy Sheet Aluminum Shell
Hinge
L
C
V
S
Aluminum Cannister Containing Food
Eyebolt for Hooking Out Heat Reservoir
Soapstone Disc Heat Reservoir
Heat Insulating Material

Fig. 108. Fig. 109.

Fig. 108.—Heat "insulators" in metallic tea-pot handle.

Fig. 109.—A fireless cooker—food in cannister V, is heated on a stove to cooking temperature. Disc, S, is likewise heated to a relatively high temperature. S and V are then inserted in cooker. Lid L is closed and clamped. Insulation minimizes loss of heat. Heat retained in cooking shell, C, is absorbed by the food. Thus the food is cooked to completion without further attention or heating.

115. The Amount Of Heat Which Will Be Transmitted Through Substances By Conduction Varies Directly As Their Cross-sectional Areas, other conditions being the same. The area is always taken at right angles to the direction of heat flow.

EXAMPLE.—A certain copper rod having a cross-sectional area of 2 sq. in. conducts 13 B.t.u. of heat in a minute. Then, other conditions remaining unchanged, a similar copper rod but of 4 sq. in. sectional area would conduct: 2 × 13 = 26 *B.t.u. in a minute*—twice the sectional area, hence twice the conduction.

116. Heat-flow By Conduction Between Two Points In A Substance Varies Directly As The Thermal Pressure, Which Is The Temperature Difference, Between Them, other conditions being the same. Just as there must be a difference of hydraulic pressure (Fig. 110) to cause water to flow in a pipe and a difference of electric pressure (voltage) to force electricity to flow in a wire, so there must be a difference of thermal pressure—or temperature—to cause heat (Fig. 111) to flow in

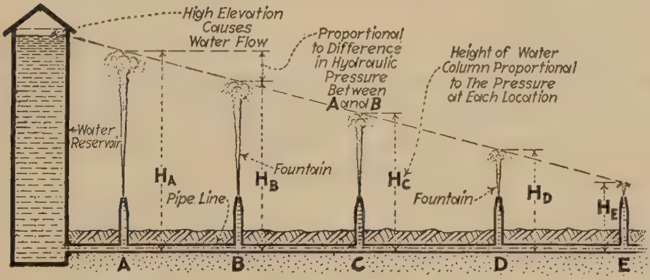

High Elevation Causes Water Flow
Proportional to Difference in Hydraulic Pressure Between A and B
Height of Water Column Proportional to The Pressure at Each Location
Water Reservoir
H_A
H_B
H_C
H_D
H_E
Pipe Line
Fountain
Fountain
A
B
C
D
E

FIG. 110.—Difference of pressure causes water to flow through pipe line. (Drop of pressure from *A* to *E* is indicated by decreasing heights of fountains. The drop of pressure is caused by friction.)

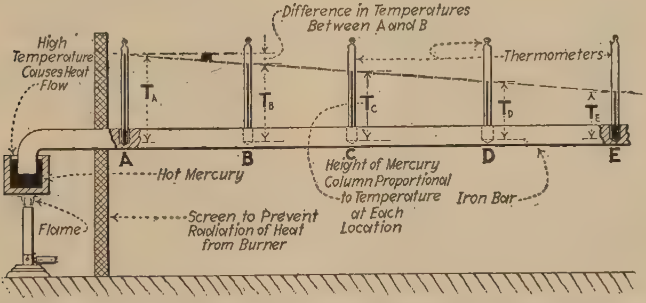

High Temperature Causes Heat Flow
Difference in Temperatures Between A and B
Thermometers
T_A
T_B
T_C
T_D
T_E
A
B
C
D
E
Hot Mercury
Height of Mercury Column Proportional to Temperature at Each Location
Iron Bar
Screen to Prevent Radiation of Heat from Burner
Flame

FIG. 111.—Difference in temperature causes heat to flow through iron bar. (Drop of temperature from *A* to *E* is indicated by decreasing heights of thermometer mercury columns. The drop in temperature is due to thermal resistance. In the above diagram it is assumed that no heat is lost from *AE* by radiation. All is conducted from the flame through and past *E* to a colder body.)

a substance. The flow is always from a point of higher to one of lower temperature.

Example.—Assume that, in Fig. 111, the temperature at *B* is 85° F. and that at *C* is 80° F. Then, the heat flow from *A* to *B* would be proportional to: 85 − 80 = 5° F. = *thermal pressure* = *temperature difference.* Suppose that, with this thermal pressure of 5° F., the heat flow from *B* to *C* is 50 B.t.u. per min. Now, if the temperature at *B* were increased to 90° and that at *C* remained at 80°, the thermal pressure would then be 90 − 80 = 10°. Hence, with the thermal pressure thus doubled, the heat flow would also be doubled and would now be: 2 × 50 = 100 *B.t.u. per min.*

117. Heat-flow By Conduction Between Two Points In A Substance Varies Directly As The Length Of Time During Which The Flow Occurs, other conditions being the same. The greater the elapsed time the greater will be the total amount of heat which is transferred.

Example.—If 40,000 B.t.u. flow from the outside to the inside of a cold-storage chamber in 1 hr., then, in 2 hr. twice the heat or, 2 × 40,000 = 80,000 *B.t.u.* will be transferred, it being assumed that temperature and all other conditions are the same in both cases.

118. Heat-flow By Conduction Between Two Points In A Substance Varies Inversely As The Length Or Distance Between The Points, other conditions being the same. The ideal condition, of no loss of heat from the substance by either radiation or convection, is here assumed. The greater the distance the less will be the flow, other conditions being equal.

Example.—If in Fig. 111 with a temperature difference of 10° F. between *A* and *C*, the heat flow between *A* and *C* is 600 *B.t.u. per min.*, then between *A* and *E*, which is twice the distance a 10° difference would force only 600 ÷ 2 = 300 *B.t.u. per min.*

119. "Thermal Conductance" is a term used to signify the ease or readiness with which a substance conducts heat. Conductance is, in a sense, the opposite (actually it is the reciprocal) of thermal resistance, which is defined in Sec. 129. The greater the conductance of a substance the more readily will it transfer heat by conduction. All substances do not conduct heat with equal facility.

Examples.—The conductance of some substances, as silver (see Table 125) is very high. That of others, as asbestos, is very low. The former are called *good heat conductors*. The latter are called *poor heat conductors* or *heat insulators*. The copper rod of Fig. 103 is a good conductor. The steel rod is, by comparison, a poor conductor. Therefore, the heat travels more rapidly through the copper than through the steel. This is indicated by the melting of the gobs of wax on the copper rod before the melting of the wax on the steel rod occurs.

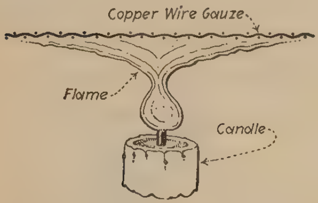


FIG. 112.—Gas burning below a copper-wire-gauze screen. The gauze conducts the heat away from the flame, thus extinguishing the flame before it can pass through the gauze.

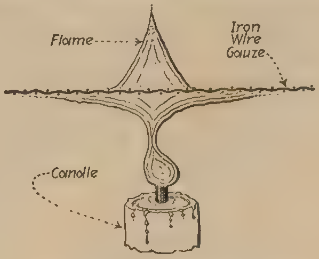


FIG. 113.—Gas burning above iron-wire gauze.

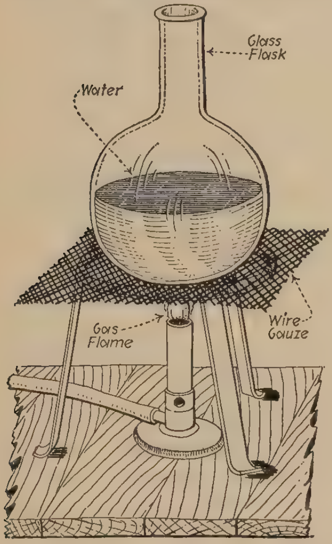


FIG. 114.—Wire gauze prevents the hot flame from touching the glass. It distributes the heat, hence the glass flask does not break.

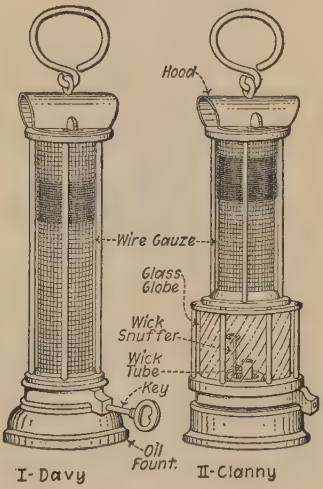


FIG. 115.—Miners' safety lamps of primitive Davy and Clanny types.

EXAMPLE.—The copper-wire-gauze screen of Fig. 112 has high thermal conductance. Therefore the heat, which is absorbed by the central area which is directly in contact with the flame, passes rapidly outward, through the surrounding area, to the edges of the screen. Hence, the central area does not retain sufficient heat to ignite the gas which penetrates above the screen. An iron-wire-gauze screen (Fig. 113) has, by comparison with the copper screen of Fig. 112, poor conductance. It follows that the heat absorbed by its area which is in contact with the flame is transmitted but slowly through the surrounding area. Hence, the central area retains sufficient heat to quickly ignite the gas which penetrates above the screen.

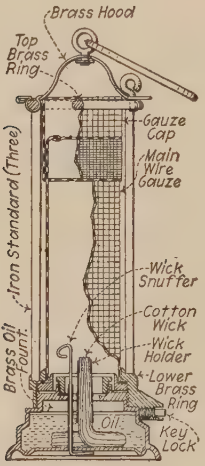


Fig. 116.—Sectional elevation of Davy lamp. (Bureau of Mines Circular No. 12.)

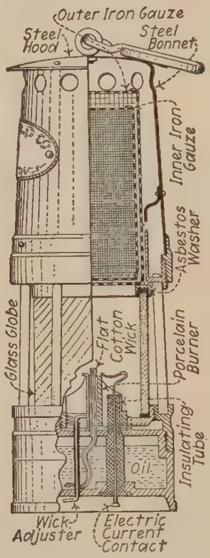


Fig. 117.—Recent bonneted pattern of Clanny-type lamp. (Bureau of Mines Circular No. 12.)

Examples.—Due to its high conductance, the copper screen (Fig. 114) distributes the heat of the gas flame over a comparatively large area beneath the glass flask. Cracking of the glass, by concentration of the heat is, thereby, prevented. Due to the high heat conductance (Fig. 112) of the metal of which they are made, the wire-gauze screens (Figs. 115, 116 and 117) which surround the flames in miners' lamps prevent ignition of explosive gases in mines.

Note.—Thermal Conductance In Heat Flow Is Somewhat Analogous To Electrical Conductance In Electricity Flow.—In fact it is generally true that substances which are good conductors of electricity are also good conductors of heat.

Note.—If The Nature Of A Substance Is Such That The Vibratory Motion Of The Molecules In That Part Of A Substance Which Is At The Higher Temperature, Is Transmitted With Great

RAPIDITY to the molecules in the cooler portions, then the conductance of the substance is high. But if the transmission proceeds sluggishly, then the conductance is low.

120. A Unit Of Thermal Conductance Is The "Moht" (pronounced, mote). *A body has a conductance of* 1 *moht when a thermal pressure—or a temperature difference—of* 1° *F. will force through it by conduction* 1 *B.t.u. per hr.* The moht is somewhat analogous to the "mho," which is the unit of electrical conductance. In following sections it is explained how the conductance, in mohts, of a given volume of a given material may be computed.

NOTE.—"MOHT" IS MERELY "THOM" SPELLED BACKWARDS. The "thom" is a unit of thermal resistance as is explained in Sec. 132. Since conductance is the reciprocal—or in a sense the opposite—of resistance, the derivation of the terminology is apparent.

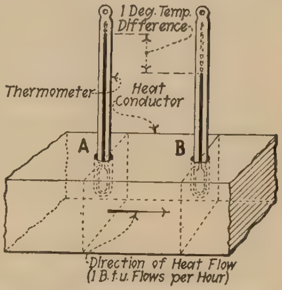


FIG. 118.—Illustrating the "moht."

EXAMPLE.—In Fig. 118 the conductance of the material between planes *A* and *B* is just 1 moht because it permits just 1 B.t.u. of heat energy to flow per hour with the thermal pressure of 1° F. This satisfies the definition of the moht.

EXAMPLE.—Fig. 119 shows some values of conductance of a square-foot-inch (1 in. thick and 1 ft. square) of some common substances. Fig. 120 shows similar values for an inch-cube. These data are taken directly from Table 125.

121. To Compute The Total Heat-energy Flow Through A Substance By Conduction When Its Conductance, In Mohts, And The Thermal Pressure Are Known, it is merely necessary to substitute in the following formula, the derivation of which will be obvious from a consideration of the preceding definitions:

$$\textit{Heat flow} = (\textit{Conductance}) \times (\textit{Thermal Pressure}) \tag{59}$$

Or, substituting for the above their equivalents as hereinbefore defined:

$$\textit{B.t.u. per hour} = \mathbf{B}(T_2 - T_1) \tag{60}$$

Then, if $\mathbf{Q}$ = total quantity of heat which flows, in B.t.u., it is apparent that:

$$\mathbf{Q} = \mathbf{B}t(T_2 - T_1) \qquad \text{(B.t.u.)} \tag{61}$$

Wherein: t = time, in hours, during which the heat flow takes place. T_2 = temperature on hot end, in degrees Fahrenheit. T_1 = temperature on cold end, in degrees Fahrenheit. **B** = the conductance, in mohts.

Example.—A slab of copper ½ in. thick and 1 ft. square has a conductance of 4,200 mohts. Then if the temperature on one side of the slab is 42° F. and that on the other is 47° F., *the total heat which flows through it in 2½ hr.* $= \mathbf{Q} = \mathbf{B}t(T_2 - T_1) = 4{,}200 \times 2.5 \times (47 - 42) = 4{,}200 \times 2.5 \times 5 = 52{,}500$ *B.t.u.*

Note.—By transposing For. (61) there result:

(62) $$\mathbf{B} = \frac{\mathbf{Q}}{t(T_2 - T_1)}$$ (mohts)

and

(63) $$(T_2 - T_1) = \frac{\mathbf{Q}}{t\,\mathbf{B}}$$ (degrees Fahrenheit)

also

(64) $$t = \frac{\mathbf{Q}}{\mathbf{B}\,(T_2 - T_1)}$$ (hours)

Example.—What is the conductance of the bar of Fig. 111 if, when the temperature at A is 800° F. and that at E is 250° F., the total heat which flows from A to E in ¼ hr. is 1,100 B.t.u.? Solution.—Substitute in For. (62): $\mathbf{B} = \mathbf{Q}/[t\,(T_2 - T_1)] = 1{,}100 \div [0.25\,(800 - 250)] = 1{,}100 \div 0.25 \times 550 = 8$ *mohts.*

Example.—What thermal pressure or temperature difference will, in 1½ hr., force 180,000 B.t.u. through a body which has a conductance of 200 mohts? Solution.—Substitute in For. (63): $(T_2 - T_1) = \mathbf{Q}/t\ \mathbf{B} = 180{,}000 \div (1.5 \times 200) = 180{,}000 \div 300 = 600°$ *F. = thermal pressure = temperature difference.*

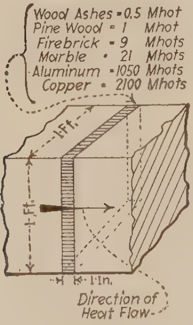


Fig. 119.—Showing conductance of some common materials, in mohts per square-foot-inch.

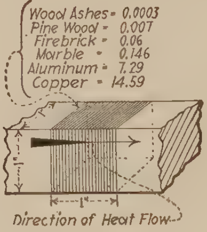


Fig. 120.—Showing conductances, in mohts per inch-cube.

122. Thermal Conductivity Is Specific Thermal Conductance.—That is, it is the conductance of a unit block of the material under consideration, which has a specified length and cross-sectional area. Frequently, in heat computations, the conductance of a slab of the material (Fig. 119) which has a sectional area of 1 sq. ft. and a thickness of 1 in., is taken as the conductivity of the material. In such cases the conductivity is expressed in mohts per square-foot-inch. The symbol K will be used herein to express conductivity.

NOTE.—SOMETIMES IT IS MORE CONVENIENT TO USE CONDUCTIVITIES WHICH ARE EXPRESSED IN MOHTS PER INCH-CUBE (Fig. 120). In any case, it is always necessary to specify the volume unit which is implied when a conductivity value is stated. How these conductivity values are applied in computations is explained in following examples.

EXAMPLES of thermal-conductivity values are given in Table 125 for various common metals, heat-insulating materials, liquids and gases.

123. The Thermal Conductivity Of A Substance Is Not Constant But Varies With The Temperature.—Strictly, values such as those given in Table 125, relate only to one temperature. But they may, without prohibitive error, be used through a reasonably wide range. Usually other variables will introduce greater errors than this variation in K.

EXAMPLE.—The same piece of metal may, under the influence of the same temperature difference, conduct heat more readily when at a high than when at a low temperature. That is, for some substances, it has been found that the value of K changes a certain amount for each change in temperature.

124. To Compute The Value Of "K" At Some Given Temperature When Its Value At Some Other Temperature Is Known the following formula may be used. Note its similarity to For. (96) for computing length of a rod at some given temperature when its length at some other temperature and its expansion coefficient are known. The same general reasoning applies in each case.

$$(65) \qquad K_T = K_O\,(1 + kT) \qquad \text{(conductivity)}$$

Wherein: K_T = value of K at any desired temperature. K_O = the known value of K at some other temperature. k = "*temperature coefficient of thermal conductivity*" = the change in value of K for each 1° change in temperature; see note below for some values of k. T = difference between the temperature at which K is known and the other temperature at which K is desired, in degrees.

Note.—Some Values For k with temperatures expressed in degrees Fahrenheit are: Aluminum, 0.000,3. Yellow brass, 0.001,36. Red brass, 0.000,89. Copper, 0.000,03. Cast iron, 0.000,83. Wrought iron, 0.000,1. Lead, 0.000,48.

Example.—At 32° F., K_S for wrought iron is known (Table 125) to be 400 mohts per sq.-ft.-in. What will K_S, for wrought iron, be at a temperature of 182° F.? Solution.—From the preceding note, k for wrought iron = 0.000,1. The *temperature difference* = 182 − 32 = 150° F. Now substitute in the formula: $K_T = K_O(1 + kT) = 400[1 + (0.000{,}1 \times 150)] = 400\ (1 + 0.015) = 400 \times 1.015 = 406$ *mohts per sq.-ft.-in.*

125. Table Showing Thermal Conductivities Of Various Substances which have been determined by experiment. There is some disagreement between the different authorities as to these values. Further research is necessary to insure complete agreement. (Quoted from various authorities: M = Marks' Mechanical Engineers' Handbook; P = Pender's Electrical Engineers' Handbook, E = Peele's Mining Engineers' Handbook; S = Smithsonian Tables. R = Randall's Practical Heat.)

Material	Ranges through which quoted values of *K* are fairly accurate		Average working conductivity values (B.t.u. per hour forced through the volume specified by a thermal pressure of 1° F.)	
	Temperatures, deg. Fahr.	Corresponding Range in actual values of K_S	K_S in mohts per sq.-ft.-in	K_I in mohts per inch-cube
Metals				
Aluminum	32–500	E 966–1,100	1,050	7.29
Brass, yellow	32–500	E 592– 216	500	3.47
Brass, red	32–500	E 713– 416	600	4.16
Copper	32–500	E 2,080–2,050	2,100	14.59
Iron, cast	32–500	E 507– 205	450	3.12
Iron, wrought	32–500	S 418– 398	400	2.78
Lead	32–500	E 242– 234	240	1.66
Steel, soft	....	S 322	320	2.22
Zinc	....	E 433	440	3.05
Insulating & Miscellaneous				
Air-cell asbestos	212–572	S 0.986–1.45	1.10	0.0076
Asbestos 44 lb./cu. ft.	−300–32	M 1.2 –1.62	1.5	0.0104
Asbestos 29 lb./cu. ft.	−300–32	M 0.654–1.07	1.0	0.0069
Brickdust, course	32–212	M 1.128	1.13	0.0078
Brickwork	68	M 3.42	3.40	0.0236
Cardboard	....	M 1.44	1.40	0.0097
Cement	95–194	P 2.06 –6.29	4.00	0.0278
Charcoal, powdered	32–212	M 0.635	6.35	0.044
Concrete	68	M 5.22 –5.64	5.50	0.038
Cotton	32–200	M 0.384–0.468	0.45	0.0031
Cork, pulverized	32–200	M 0.252–0.384	0.30	0.0021
Felt	....	M 0.264	0.26	0.0018
Firebrick	32–2,400	M 9.0	9.0	0.0625
Firebrick, powdered	70–212	M 0.815	0.82	0.0057
Glass, crown, window	....	M 7.2	7.00	0.0486
Linoleum	68	M 1.28	1.25	0.0087
Magnesia	70–212	M 1.31	1.30	0.0090
Marble	....	M 20.6	21.00	0.146
Mica	....	M 5.28	5.25	0.0365
Mill shavings	....	M 0.6	0.6	0.0042
Paper	....	M 0.9	0.9	0.0063
Porcelain	....	M 7.2	7.20	0.0500
Rubber, Para	....	M 1.31	1.30	0.0090
Sand	68–311	P 2.48 –2.51	2.50	0.0174
Sawdust	70–275	M 0.444	0.45	0.0031
Scale, boiler	....	R 16.0	16.00	0.111
Slate	....	M 13.7	14.00	0.0972
Wood ashes	32–212	M 48	0.50	0.0035
Wood, oak, to fiber	68	M 1.44	1.40	0.0097
Wood, pine, to fiber	68	M 1.04	1.00	0.0069
Wool, sheep	68–212	P 0.365–0.441	0.40	0.0028
Wool, mineral	....	....	0.42	0.0029
Liquids				
Water	....	P 3.5–6.5	4.50	0.0312
Brine	39	S 3.35	3.30	0.0229
Gases				
Ammonia	32–212	P 0.133–0.206	0.15	0.0010
Air	32	M 0.151	0.15	0.0010

126. To Compute The Thermal Conductance Of Any Volume Of Any Given Substance, substitute in the following formula, the derivation of which is given below:

$$\text{(66)} \qquad \mathbf{B} = \frac{K_S A}{L} \qquad \text{(mohts)}$$

and it follows that:

$$\text{(67)} \qquad K_S = \frac{\mathbf{B}L}{A} \qquad \text{(mohts per sq.-ft.-in.)}$$

or

$$\text{(68)} \qquad A = \frac{\mathbf{B}L}{K_S} \qquad \text{(square feet)}$$

also

$$\text{(69)} \qquad L = \frac{K_S A}{\mathbf{B}} \qquad \text{(feet)}$$

Wherein: $\mathbf{B}$ = thermal conductance, in mohts, as defined in preceding Sec. 120. K_S = thermal conductivity of the substance, in mohts per square-foot-inch; see Table 125 for values. A = area of the substance, taken at right angles to the direction of heat flow, in square feet. L = length or thickness of the substance, in a direction parallel to the direction of heat flow, in inches.

Derivation.—As defined in Sec. 120, the *moht* is the conductance of a body which will permit 1 B.t.u. per hour to flow through it when the thermal pressure is 1° F. It has also been explained that the heat flow through a substance varies: (1) *Directly as the cross-sectional area* (Sec. 115). (2) *Inversely as the length* (Sec. 118). Now the values in the K_S column of Table 125 are the conductances from face to face, in mohts, of slabs, of different substances, 1 sq. ft. in cross-sectional area and 1 in. thick. These values have been determined by experiment. Hence, it follows that if, for any given volume of a certain substance having given dimensions, the K_S value for the substance from Table 124 is multiplied by the sectional area of the volume in square feet and the result then divided by its length (thickness) in inches, the result will be the mohts conductance of that volume when it has the given dimensions. These operations are those which are specified by For. (66).

Example.—What is the thermal conductance in mohts, from face to face, of a slab of wrought-iron boiler plate which is ½ in. thick and 8 sq. ft. in area? Solution.—From Table 125, K_S for wrought iron is 400. Now substitute in For. (66): $\mathbf{B} = K_S A/L = 400 \times 8 \div 0.5 = 6{,}400$ *mohts.*

Note.—If Conductivity Values In Mohts Per Inch-cube Are Used from the K_I column of Table 125, then the equivalent of For. (66) becomes:

$$\text{(70)} \qquad \mathbf{B} = \frac{K_I A_I}{L} \qquad \text{(mohts)}$$

Wherein: K_I = thermal conductivity of the substance, in mohts per inch-cube. A_I = area of the substance taken at right angles to the direction of heat flow, in square inches. L = length or thickness of the substance in a direction parallel to the direction of heat flow, in inches.

NOTE.—WHEN THE CONDUCTANCE OF A BODY IN MOHTS HAS BEEN DETERMINED, the amount of heat which will flow through it in a given time, under a given thermal pressure or temperature difference, may be computed by substituting in For. (61).

127. A Formula For Computing The Total Flow Of Heat Energy By Conduction Through Any Volume Of A Given Substance, When Its Area, And Length And The Time And Thermal Pressure Are Known is given below. Its derivation follows the formula.

$$Q = \frac{K_S A(T_2 - T_1)t}{L} \qquad \text{(British thermal units)} \tag{71}$$

Wherein all of the symbols have the same meanings as those specified in Secs. 121 and 126.

DERIVATION.—From For. (61), $Q = Bt(T_2 - T_1)$. But from For. (66): $B = K_S A/L$. Now substituting for B in For. (61), its equivalent from For. (66), there results: $Q = K_S A(T_2 - T_1)t/L$, which is For. (71). Usually, it is preferable to use For. (61) instead of (71), first finding the *mohts conductance* with For. (66).

EXAMPLE.—What quantity of heat will flow, in 1½ hr., through a layer of boiler scale ½ in. thick and 10 sq. ft. in area when the temperature on the outside of the scale is 875° F. and the temperature on the inside of the scale is 375° F.? SOLUTION.—From Table 125, K_S for boiler scale is 16 *mohts per sq.-ft.-in.* Now substitute in For. (71): $Q = K_S A(T_2 - T_1)t/L = [16 \times 10(875 - 375)1.5] \div 0.5 = 160 \times 500 \times 1.5 \div 0.5 =$ 240,000 *B.t.u.*

128. A Formula For Computing The Rate Of Heat-energy Flow—That Is, The Power Flow—By Conduction through any volume of a given substance is (see derivation below):

$$\textit{B.t.u. per hr.} = B(T_2 - T_1) \qquad \text{(B.t.u. per hr.)} \tag{72}$$

or if, as in electric-furnace and other electrical-apparatus computations, it is desirable to express the rate of heat energy flow in *watts*, then:

$$\textit{Watts} = 0.293\ B\ (T_2 - T_1) \qquad \text{(watts)} \tag{73}$$

The thermal conductance of the volume of the substance in question may be computed as explained in Sec. 126.

DERIVATION.—From For. (61): $Q = Bt(T_2 - T_1)$. Now, to obtain the rate of heat flow per hour, divide For. (61) through by the time in hours, that is by t, thus:

$$(74) \qquad B.t.u.\ per\ hr. = \frac{Q}{t} = \frac{Bt(T_2 - T_1)}{t} = B(T_2 - T_1)$$

Also, since a rate of energy expenditure of 1 *watt* = 3.415 *B.t.u. per hr.*, to convert "*B.t.u. per hr.*" expression of For. (74) into watts, divide by 3.415, thus:

$$(75) \qquad Watts = \frac{B(T_2 - T_1)}{3.415} = 0.293\ B(T_2 - T_1)$$

129. "Thermal Resistance" is, in a sense, the opposite of thermal conductance, which is defined in Sec. 119. While *conductance* expresses the readiness with which a material conducts heat, *resistance* expresses the opposition which a material offers to heat flow. The greater the conductance, the greater the heat flow, but the greater the resistance the less the heat flow.

NOTE.—NUMERICALLY, HEAT RESISTANCE IS THE RECIPROCAL OF HEAT CONDUCTANCE AND VICE VERSA.—That is, if a substance has a heat conductance of 10 *units*, its heat resistance is: 1 ÷ 10 = 0.1 *units*. These quantities are analogous respectively to electrical resistance and electrical conductance. Thermal resistance to heat flow is also somewhat analogous to the frictional resistance offered by the interior surface of a pipe to the flow of water through it.

NOTE.—THE THERMAL RESISTANCE OF A SUBSTANCE IS LOW if the construction and arrangement of the molecules of the substance is such that heat which is imparted to one part of the substance is transmitted with great rapidity to the molecules in the cooler portions. But if the transmission proceeds only sluggishly, then the resistance is high.

130. Internal Thermal Resistance is the opposition to heat transfer which occurs within the substance. It is, numerically, the reciprocal of internal thermal conductance.

131. External—Or Contact—Thermal Resistance is the resistance to heat transfer which occurs between two substances which are in contact with each other. Definite quantitative data relating to this form of resistance are not available.

NOTE.—RESISTANCE TO THE FLOW OF HEAT FROM THE GASES OF COMBUSTION IN A BOILER FURNACE TO THE WATER IN A BOILER is, largely, due to the contact resistance between the gases and the steel boiler-shell or tubes, and between the shell or tubes and the water. It is also due to the internal resistance of the plate itself, the resistance of a stagnant gas film on one side of the boiler plate, and the resistance of a stagnant water film on the other side.

132. A Unit Of Thermal Resistance Is The "Thom."—This word is merely a contraction of the term "*thermal ohm.*" See, in this connection, Sec. 120 in which the "*moht*" is defined. A body has a resistance of 1 thom when a thermal pressure—or temperature difference—of 1° F. will force heat through it, by conduction, at the rate of 1 B.t.u. per hour.

133. To Compute The Total Heat-energy Flow Through A Substance When Its Resistance, In Thoms, And The Thermal Pressure Are Known, substitute in the following formula, the derivation of which follows from the definition of preceding Sec. 132.

$$\text{(76)} \qquad B.t.u.\ per\ hour = \frac{Thermal\ pressure}{Thermal\ resistance}$$

or substituting for the above quantities their equivalents as hereinbefore defined:

$$\text{(77)} \qquad B.t.u.\ per\ hour = \frac{(T_2 - T_1)}{\mathbf{R}}$$

Wherein: **R** = the thermal resistance, in thoms. The above equation expresses what is sometimes called the *Ohm's law of the heat-flow circuit.* Now if **Q** = the total quantity of heat which flows, in B.t.u., it is apparent that:

$$\text{(78)} \qquad \mathbf{Q} = \frac{(T_2 - T_1)t}{\mathbf{R}} \qquad \text{(B.t.u.)}$$

EXAMPLE.—A certain slab of copper has a thermal resistance of 0.000,238 thoms. If the temperature on one side of the slab is 42° F., and that on the other is 47° F., what will be the total heat which will flow through it in 2½ hr.? SOLUTION.—Substitute in For. (78): $\mathbf{Q} = [(T_2 - T_1)t]/\mathbf{R} = [(47 - 42)2.5] \div 0.000,238 = 5 \times 2.5 \div 0.000,238 = 52,500$ *B.t.u.* Compare this example with that under For. (61).

134. Thermal Resistivity Is Specific Thermal Resistance.—That is, it is the resistance of a block of the material, which is under consideration, which has a specified length and cross-sectional area. Numerically, a thermal-resistivity value will be the reciprocal of the corresponding thermal-conductivity value. Review Sec. 122 on "Thermal Conductivity." To obtain the thermal resistivities of the materials which are listed in Table 125, in thoms per *square-foot-inch*—or per *inch-*

cube—compute the reciprocals of the corresponding conductivity values there quoted.

NOTE.—THERMAL-RESISTIVITY VALUES ARE NOT GIVEN IN TABLE 125 because it is usually, when computing, more convenient to use the conductivity values. In many cases, the resistivity values would be long awkward decimals. Equally correct results may be obtained by using either resistivity or conductivity values, if the proper formula is utilized in each case.

135. To Compute The Thermal Resistance Of A Volume Of A Substance In Thoms, first determine its conductance in mohts as specified in For. (66) and then figure the reciprocal of the value thus obtained. This last value will be the thermal resistance, in thoms.

EXAMPLE.—The thermal conductance of a certain slab of copper is 4,200 mohts. Therefore, *its thermal resistance is:* 1 ÷ 4,200 = 0.000,238 *thoms.*

136. To Compute The Rate Of Heat-energy Flow, That Is, The Power Flow, Through A Substance When Its Thermal Resistance, In Thoms, Is Known, the formulas quoted below may be employed. These, since *resistance* is the reciprocal of *conductance*, follow from Fors. (72) and (73).

$$\text{(79)} \qquad B.t.u.\ per\ hour = \frac{T_2 - T_1}{\mathbf{R}}$$

and

$$\text{(80)} \qquad Watts = \frac{0.293(T_2 - T_1)}{\mathbf{R}}$$

EXAMPLE.—What will be the heat power loss, in watts, through the heat-insulating jacket of a furnace, if the thermal resistance of the jacket is 0.003 thoms and inside and outside temperatures are respectively 1,700 and 180° F.? SOLUTION.—Substitute in For. (80): $Watts = [0.293(T_2 - T_1)]/\mathbf{R} = [0.293 \times (1{,}700 - 180)] \div 0.003 = 0.293 \times 1{,}520 \div 0.003 =$ 148,400 *watts.*

137. Convection Is Transfer Of Heat By The Flow Of Currents Within A Fluid Body.—The current-flow is due to variations of density, caused by inequalities of expansion and contraction, through the fluid body.

EXPLANATION.—When any portion of a fluid, as air, becomes heated (Fig. 121), it expands, (Sec. 159). The density of that portion of the fluid diminishes. A given volume of it becomes lighter than it was before. That is, the volume of a given weight of the fluid becomes greater. According as the density of any portion of a fluid, as water (Figs. 122, 123, 124, and 125), diminishes, due to conduction of heat to that portion of the fluid, it rises and is displaced by the cooler, more dense and heavier surrounding portions of the fluid. These portions, in turn, likewise become

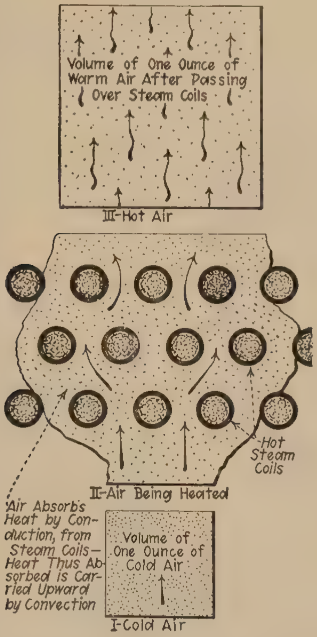

Volume of One Ounce of Warm Air After Passing Over Steam Coils
III-Hot Air
Hot Steam Coils
II-Air Being Heated
Air Absorbs Heat by Conduction, from Steam Coils—Heat Thus Absorbed is Carried Upward by Convection
Volume of One Ounce of Cold Air
I-Cold Air

Fig. 121.—Showing the increase in volume of a certain mass (weight) of air in passing over hot steam coils.

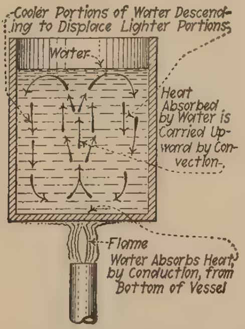

Cooler Portions of Water Descending to Displace Lighter Portions
Water
Heat Absorbed by Water is Carried Upward by Convection
Flame
Water Absorbs Heat by Conduction, from Bottom of Vessel

Fig. 122.—Water circulation when heat is applied to center of a vessel.

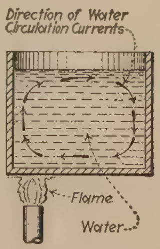


Fig. 123.—Water circulation in vessel heated on one side.

heated and displaced. Continuous circulating currents are thus set up in the fluid. Heat is thereby transferred, by convection, from the parts of the containing vessels which are in direct contact with the sources of heat to the parts which are remote therefrom.

Hot water is admitted (Fig. 126) to a cold cast-iron radiator, R. The

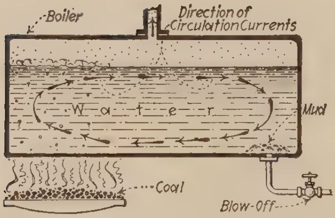


Fig. 124.—Showing water circulation in ordinary cylindrical drum boiler.

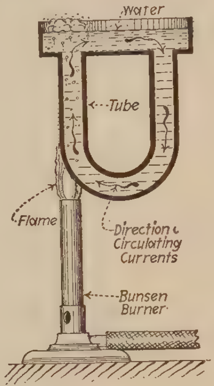


Fig. 125.—Showing circulation in a U-tube when one leg is heated.

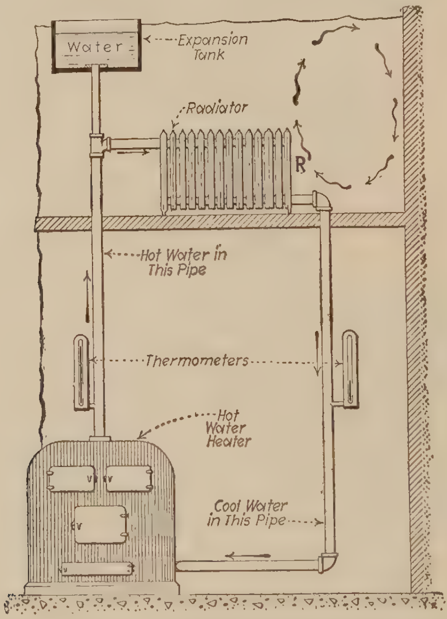


Fig. 126.—Hot-water heating system.

heat in the water is transferred, by conduction, to the iron walls of the radiator. Then the heat in the iron is transferred, by conduction, to the particles of external air which are directly in contact with the radiator. This air expands. Its density diminishes. It becomes lighter, per unit of volume, than it was a moment previous. It is displaced from contact with the radiator by the heavier air below it. Similarly other portions of air become heated, expanded, diminished in density and displaced from contact with the radiator. A continuous convection-current, which carries the heat to the parts of the enclosed space which are remote from the radiator is thus set up. This current constantly imparts its heat, by conduction, to the remote bodies with which it makes contact, and constantly returns to the radiator for a fresh supply. Some heat is also transmitted from a radiator by *radiation* (Sec. 138).

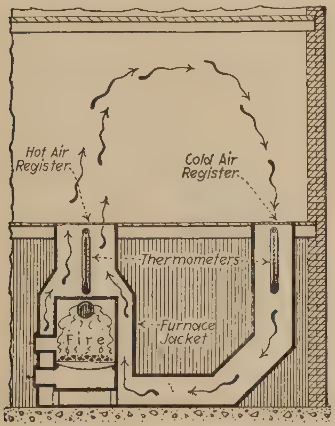


Fig. 127.—Heating with a warm-air furnace.

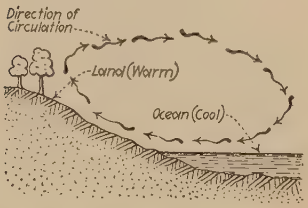


Fig 128.—Showing convection currents of air at junction of ocean and land. (Direction of flow may be reversed when the land is the cooler.)

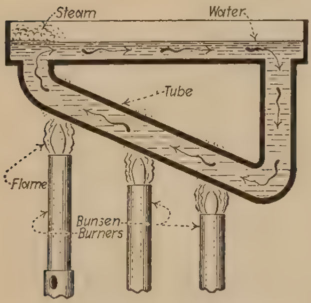


Fig. 129.—Showing circulation in inclined tube.

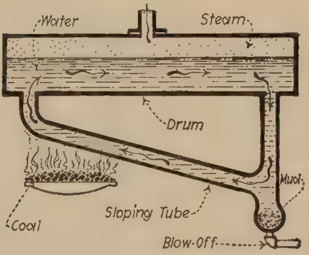


Fig. 130.—Showing water circulation in simple water-tube boiler.

Note.—Transfer Of Heat By Convection Is Utilized In Many Ways.—The effectiveness of hot-water (Fig. 126), steam, and hot-air (Fig. 127) heating systems (Div. 17), of ventilating systems, and of chimneys and stacks (Sec. 256) depends upon this principle. To it, also, are due the winds (Fig. 128) which traverse land and sea. Convection is of fundamental importance in the operation of steam boilers. The tubes of horizontal water-tube boilers are set (Figs. 129 and 130) at an inclination to the horizontal. The object is to facilitate transfer of heat by convection. Rapid circulation of the water-currents, and, therefore, of heat-transfer by convection is (Figs. 131 and 132) one of the foremost considerations in boiler design. The principle of convection is, often, utilized (Fig. 133) in the natural ventilation of buildings.

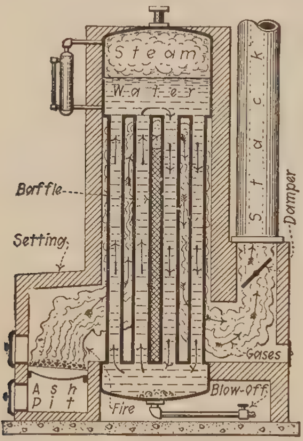


FIG. 131.—Water and gas circulation in one type of vertical water-tube boiler.

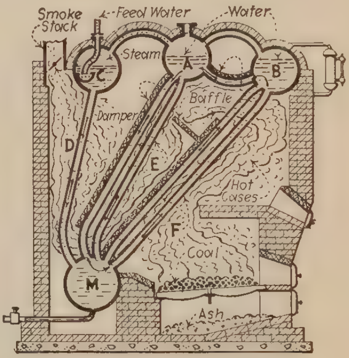


FIG. 132.—Showing water and gas circulation in Stirling-type boiler.

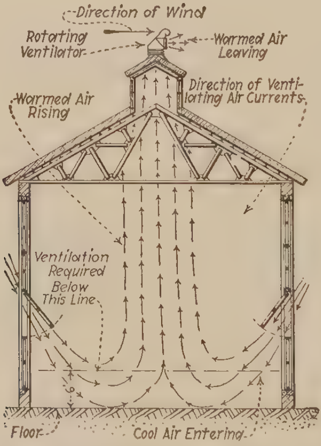


FIG. 133.—Ventilation due to convection. (This shows a scientific arrangement Note movement of air near floor where employes work. The wind, if there is any, assists in promoting circulation.)

NOTE.—THE MATHEMATICS OF HEAT TRANSFER BY CONVECTION IS RATHER COMPLICATED.—It involves consideration of many factors, as temperatures, specific heats, densities, viscosities, and probably others. Hence, no formulæ pertaining to this subject will be given herein. How a chimney produces *draft* by convection is explained in Sec. 256 and in the author's STEAM BOILERS.

138. Radiation Is Transfer Of Heat From One Body To Another By Wave Motion In The Æther (Sec. 46). When being thus transferred by wave motion in the æther, the energy is called radiant heat energy or merely radiant heat. Radiant heat is, therefore, wave motion and not molecular motion as is heat in its most common form. The earth receives the sun's heat by radiation. The æther which fills interstellar space, and, in fact, all space unoccupied by matter, is the medium of transmission.

EXPLANATION.—If the bare hand be suddenly thrust before the open door of a boiler-furnace, within which an intensely hot fire is burning, an unbearable sensation of heat will be felt instantly. Evidently, this can be due neither (Sec. 137) to convection nor (Sec. 111) to conduction. It cannot be accounted for on the principle of convection, because the convection-current flow will be inward, instead of outward, through the furnace-door. The exposed hand will be constantly bathed by an air-current flowing into the furnace from the comparatively cool atmosphere of the room. For the same reason, the intense sensation of heat cannot be accounted for on the principle of conduction. Even if the air in contact with the hand were to become temporarily stagnant, a considerable interval of time would still be required for it to conduct the heat thereto, because air is (Sec. 114) a poor conductor of heat.

The true explanation is, that the vibratory heat motion, of the molecules of the combustibles in the furnace, sets up a wave motion in the æther which (Sec. 46) fills the interstices between the air molecules. These heat waves travel, at enormous speed (Sec. 178), along straight lines which radiate in all directions from the source of heat. They tend to reproduce (Sec. 142), in all matter which lies in their path, the vibratory heat motion of the heated substance wherein they originate. Those which travel in the direction of the exposed hand before the furnace door, traverse the intervening distance in an interval of time which is so brief as to be virtually instantaneous. In fact, radiant heat waves travel at the same speed as do light waves, viz.: 186,000 miles per sec., as explained in Sec. 178.

139. Heat May Be Radiated Through Vacua.—The heat energy of the sun passes through a presumably perfect vacuum, millions of miles in extent, before it reaches the earth's atmosphere.

NOTE.—HEAT CAN NEITHER BE CONDUCTED NOR CONVECTED THROUGH A VACUUM.—In a space wherein matter is nonexistent, both the molecular motion by which heat is conducted, and the current-flow by which it may be convected, must likewise be nonexistent.

EXAMPLE.—A glass vessel enclosing a practically perfect vacuum might be interposed between the bare hand and the fire in the furnace. But the sensation of heat would still be felt.

140. Heat Waves May Be Visible Or Invisible.—Those which are visible are (Sec. 176) classed as light waves. The quality of visibility depends upon the degree of heat (temperature) which is possessed by the bodies from which the waves emanate.

EXAMPLE.—A mass of iron when heated to about 480° F. will, in a dark room, give off visible heat waves. When the temperature of the iron drops below 480° F., the heat waves will become invisible.

141. Heat May Be Radiated Through Transparent Or Translucent Bodies To Other Bodies Beyond.—Some substances tend (Sec. 143) to absorb heat waves more readily than do certain other substances.

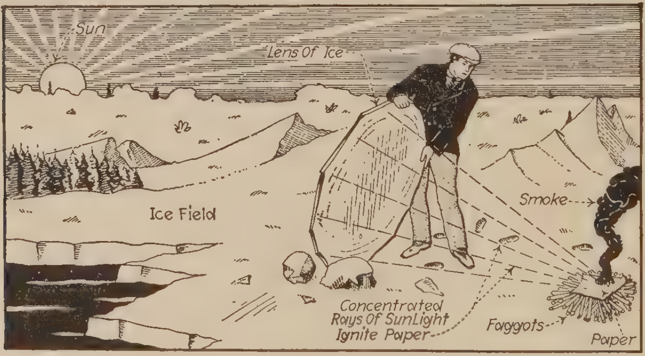


FIG. 134.—Lens of ice shaped like a burning glass concentrates radiant heat waves of sun and ignites paper.

EXAMPLE.—The visible heat waves, which (Fig. 134) are manifested in the sun's rays, tend to stimulate heat motion in the lens-shaped cake of ice. Presently the ice lens will be melted to water. But while the lens continues intact, the heat waves passing through it will, by being focused or concentrated on the faggots, ignite them.

142. Radiant Energy Is That Form Of Energy Which Resides In Æthereal Heat Waves.—It is the essence of the phenomenon which (Sec. 138) is conveniently defined as transfer of heat by radiation, or as *radiant heat.*

Explanation.—The earth receives the sun's heat by radiation. But the sun's heat exists as a vibration of the molecules of the sun's substance. This vibratory molecular motion, or heat, cannot be imparted by conduction to the æther which lies between the sun and the earth and thence to the molecules of the earth's substance—the æther has no molecular structure to receive it. Therefore, it is an obvious misnomer to consider the phenomenon of radiation as a direct transfer of actual heat by contact.

The energy of the sun's molecular vibration, or heat, is, however, imparted to the æther. This transfer of energy is manifested by waves which are thereby made to traverse the æther. These waves radiate from the sun along straight lines (Sec. 138). They are waves of radiant energy. When a mass of matter, as the earth, intercepts their path, they impress their radiant energy or a portion of it on that mass of matter and thereby reproduce therein the molecular motion, or heat, to which they owe their origin.

143. Waves Of Radiant Energy Are Converted Into Heat In The Material Bodies Which Intercept Them.—Radiant energy tends, more or less, to penetrate (Sec. 141) substances which are transparent, translucent or opaque to light, as respectively a window-pane, a draftsman's celluloid triangle, or a china cup. The ability of any of these substances to convert radiant energy into heat is inversely proportional to its capacity for transmitting light. An ideally transparent substance would convert none of the radiant heat energy which impinged on it to molecular-vibration heat energy; all would pass through. An absolutely opaque non-reflecting substance would convert all radiant energy which impinged on it to molecular-vibration heat energy. Radiant energy cannot penetrate substances into which light cannot enter. The radiant energy, or a portion of it, is transformed into heat among the surface molecules of such substances. Then the heat is carried, by conduction, throughout the body of the substance. The more impenetrable the substance, the greater its capacity for conversion of radiant energy into heat.

Note.—Dull Black Surfaces Of Bodies Are The Best Converters Of Radiant Energy.—They are also the best radiators thereof. It is presumed that if a surface, in which the qualities of blackness and dullness would be perfectly blended, could be prepared, the surface would absorb, and convert into heat, all of the radiant energy which it might intercept. A surface coated with lampblack is probably the nearest approach to the ideally perfect absorbing surface.

144. Radiant Energy Which Is Intercepted By A Material Body May Be Reflected Therefrom (Figs. 135, 136 and 137). Some of the heat waves which impinge upon the surface of the body will (Sec. 138) become transformed into molecular motion or heat. But others may rebound. *The angle of incidence, I,* (Fig. 135) is always equal to *the angle of reflection, R.*

NOTE.—BRIGHTLY POLISHED SURFACES REFLECT RADIANT ENERGY VERY READILY.—Thereby they tend to prevent the absorption of radiant heat by any body which they surround. Conversely, polished surfaces are poor radiators of heat thereby they tend to prevent loss of radiant heat from bodies which they surround. A bright silvery surface (Figs. 135 and 137) will reflect most of the radiant energy which it may

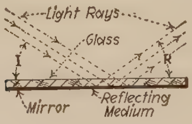


FIG. 135.—Heat waves are reflected in the same manner as are light waves.

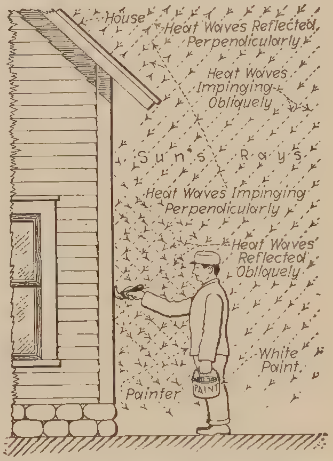

House
Heat Waves Reflected Perpendicularly
Heat Waves Impinging Obliquely
Sun's Rays
Heat Waves Impinging Perpendicularly
Heat Waves Reflected Obliquely
White Paint
Painter
PAINT

FIG. 136.—Reflected radiant energy from the sun makes it hot for the painter.

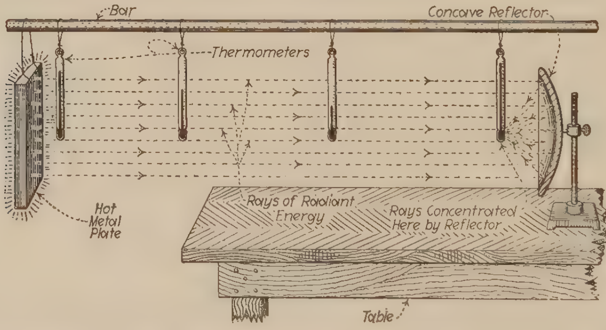


FIG. 137.—Radiant-energy heat rays are reflected and focused by a concave mirror in the same manner as are light rays.

intercept. A white painted surface (Fig. 136) would, by reflection, produce a much more uncomfortable heating effect than would a black surface.

145. Surfaces Which Are Good Radiators Of Radiant Heat Are Also Good Absorbers Thereof. Surfaces Which Are Poor Radiators Are Good Reflectors.—These facts may (Figs. 138 and 139) be readily demonstrated by experiment. Advantage of them is taken in many practical applications.

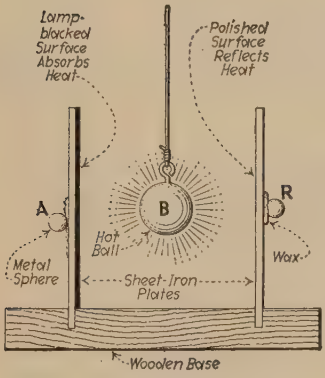

Lamp-blacked Surface Absorbs Heat
Polished Surface Reflects Heat
A
B
R
Hot Ball
Metal Sphere
Wax
Sheet-Iron Plates
Wooden Base

FIG. 138.—Good heat reflectors are poor heat absorbers and vice versa.

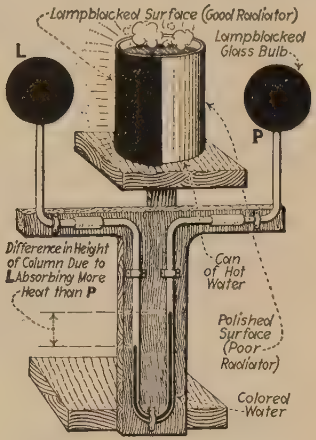

Lampblacked Surface (Good Radiator)
Lampblacked Glass Bulb
L
P
Difference in Height of Column Due to L Absorbing More Heat than P
Can of Hot Water
Polished Surface (Poor Radiator)
Colored Water

FIG. 139.—Good heat absorbers are good heat radiators.

In general, the rough dark surfaces are good radiators and absorbers; smooth polished light surfaces are good reflectors and poor absorbers.

EXAMPLE.—In Fig. 138, the metal sphere, *A*, on the lampblacked plate will melt off before that, *R*, on the polished plate melts off. The lampblacked plate quickly absorbs radiant heat from the hot metal ball, *B*. The polished plate reflects the heat away. In Fig. 139, the bulb, *L*, absorbs more heat than does *P*, because the lampblacked side of the hot-water-can radiates heat much more rapidly than does the polished side.

EXAMPLE.—The metal casings of "thermos" bottles (Figs. 106 and 107) are often nickeled and polished on the outside to minimize the loss or gain of heat by them by radiation. The glass container inside such a bottle is similarly coated like a mirror for the same reason. Likewise calorimeter vessels (Fig. 95) are, usually, of polished nickel. Electric heaters (Fig. 82) have highly polished reflectors. Steam-heating-system radiators (Sec. 590) are, purposely, left rough outside to promote radiation of heat from them.

146. Radiant Energy Is Susceptible To Refraction.—This is observed when visible heat waves, in the form of rays of sunlight, are (Figs. 134 and 140) caused to pass through a convex lens. A refractive, or bending, effect is also observed (Figs. 141 and 142) when visible heat waves, or light rays, pass through the bounding surfaces of transparent substances, as clear water or glass.

NOTE.—RADIANT HEAT WAVES MAY THEREFORE BE CONCENTRATED WITH A LENS (Figs. 134 and 140) in about the same way that light waves can be concentrated.

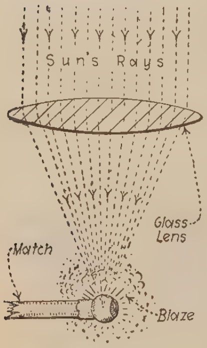


FIG. 140.—Sun's rays are refracted by the lens and concentrated on the head of a match, igniting it.

147. The Radiant Heat Which Is Given Off By A Body may be computed by the Stefan-Boltzmann formula, which is as follows:

$$Q = kAt\left(\frac{T}{100}\right)^4 \qquad \text{(British thermal units)} \tag{81}$$

Wherein: **Q** = the quantity of heat, in British thermal units, which is radiated. k = a constant for the material, taken from Table 149. A = the area of the radiating surface, in square feet. t = the time interval, in hours, during which the radiation occurs. **T** = the absolute temperature

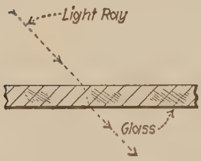


FIG. 141.—The course of a ray of light is changed by refraction when it passes through the common surface of two transparent mediums of different density.

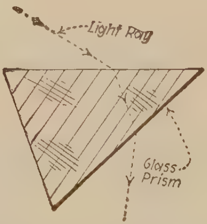


FIG. 142.—Path of a light ray is deflected when passing through a prism.

of the body, in degrees Fahrenheit = reading of the observed temperature + 460.

For a radiator possessing absolute blackness, For. (81) becomes:

$$Q = 0.161{,}8At\left(\frac{T}{100}\right)^4 \qquad \text{(British thermal units)} \tag{82}$$

148. The Net Heat-transfer, By Radiation, Between A Hot Surface And A Parallel Cool Surface (both surfaces must be very large, of the same size, and one of them a perfectly black body, Fig. 143) may be computed by the following adaptation of the Stefan-Boltzmann formula:

$$Q_R = k\left[\left(\frac{T_1}{100}\right)^4 - \left(\frac{T_2}{100}\right)^4\right] \qquad \text{(B.t.u. per hr. per sq. ft.)} \tag{83}$$

Wherein: Q_R = quantity of heat transferred, in British thermal units, per hour per square foot of area (*A* or *B*, Fig. 143) of either surface. k = a constant for the material, taken from Table 149. T_1 and T_2 = respectively, the absolute temperatures in degrees Fahrenheit, of the hot and cold surfaces = reading of the observed temperature of each surface + 460. This formula illustrates the principal of mutual radiation. However, in practice very few cases arise in which the radiation is between two large parallel surfaces of equal area, one of which is a perfectly black body. Hence, the formula can seldom be used for accurate solutions. But

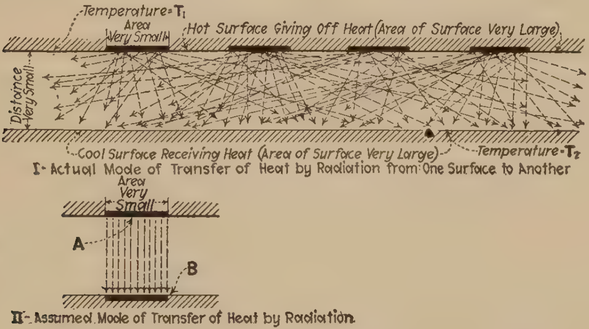

Temperature = T_1
Area Very Small
Hot Surface Giving Off Heat (Area of Surface Very Large)
Distance Very Small
Cool Surface Receiving Heat (Area of Surface Very Large)
Temperature = T_2
I - Actual Mode of Transfer of Heat by Radiation from One Surface to Another
Area Very Small
A
B
II - Assumed Mode of Transfer of Heat by Radiation

FIG. 143.—Showing how heat actually radiates, and how, for the purposes of computation, it is assumed to radiate. (In *II* it is assumed that all heat is radiated at right angles to the surfaces. This is assumed to be true only when the surfaces are very large.)

it can be used in most cases, such as in boiler furnaces, for calculating approximately the heat which radiates from a square foot of an incandescent body.

149. Table Showing Values Of The Radiation Constant k For Various Materials (From Marks' MECHANICAL ENGINEERS' HANDBOOK).

Material	k	Temp., deg. Fahr.	Material	k	Temp., deg. Fahr.
Ideally black body	0.1618	70	Zinc, dull	0.034	120–545
Glass, smooth	0.154	.....	Cast iron, rough, highly oxidized	0.157	105–480
Brass, dull	0.0362	100–660	Lime plaster, rough white	0.151	150–195
Lampblack	0.154	32–100	Slate, smooth	0.115	140–400
Copper, slightly polished	0.0278	100–540	Field soil	0.063	140–400
Wrought iron, dull, oxidized	0.154	70–670	Water	0.112	140
Wrought iron, (ordinary black body)	0.0562	85–225	Ice	0.106	32
Wrought iron, highly polished	0.0467	105–480	Incandescent bodies	0.155	

150. Radiant Heat Within A Boiler Furnace will now be considered. A boiler receives little heat by radiation from the gases of combustion. It may receive some heat by radiation from the long tongues of luminous flame which result from burning highly volatile bituminous coals. But most of the heat delivered to a boiler by radiation comes from the glowing and incandescent fuel on the grate, and from the highly heated fire-brick lining of the furnace. For a given grate area neither the contour of the portion of the boiler surface which receives the radiant heat, nor (within reasonable limits) the distance of the surface from the fuel bed, have any apparent influence on the amount of heat thus transferred to the boiler shell by radiation.

EXAMPLE.—The temperature of the incandescent fuel bed, and of the fire-brick lining, in a boiler furnace, is 2,300° F. The temperature of the boiler shell is 600° F. If the furnace temperature be raised to 2,500° F., what will be the increase in the quantity of heat transferred to the boiler shell by radiation? SOLUTION.—k for wrought-iron bodies (Table 149) = 0.154. By For. (83), *the heat radiated under the prevailing furnace temperature* $Q_R = k\,[(T_1/100)^4 - (T_2/100)^4] = 0.154 \times \{[(2{,}300 +$

460) ÷ 100]^4 − [(600 + 460) ÷ 100]^4} = 87,400 *B.t.u. per hr. per sq. ft. of the area of the hot surface which radiates the heat.* Also, by For. (83) *the heat which would be radiated under the increased furnace temperature* = $Q_R = k\,[(T_1/100)^4 - (T_2/100)^4]$ = 0.154 × {[(2,500 + 460) ÷ 100)]^4 − [(600 + 460) ÷ 100]^4} = 116,300 *B.t.u. per hr. per sq. ft. of the area of the hot surface which radiates the heat.* Hence, *the increase in the quantity of heat radiated* = 116,300 − 87,400 = 28,900 *B.t.u. per hr. per sq. ft. of the area of the hot fuel bed.*

151. The Problem Of Heat Radiation In Boiler Furnaces Is Very Complicated.—This is particularly true of the radiation which occurs in the furnaces of externally fired boilers. It is beyond the province of this book to go into the abstruse mathematics of the subject. Enough has been shown, however, in the preceding example to emphasize the advantage, in boiler operation, of maintaining high furnace temperatures. As indicated in the solution of the preceding example, the quantity of heat which a boiler receives by radiation increases very rapidly as the furnace temperature rises.

EXAMPLES.—By increasing the furnace temperature from 2,000° F. to 3,000° F., the quantity of heat which is delivered to a boiler by radiation under the lower temperature, may be increased approximately four times. By permitting the temperature to fall from 2,500° F. to 2,400° F., the quantity of radiant heat may be diminished about 12 per cent. The fusing temperature of the ash generally limits the maximum attainable temperature of the fire in a boiler furnace.

152. Heat Transfer May Be Effected By Simultaneous Occurrence Of Conduction, Convection And Radiation.—When the three modes of heat-transfer thus act conjointly to deliver heat to a substance, the resulting phenomena are very complicated and difficult of exact analysis.

EXPLANATION.—In boiler operation, the furnace heat (Fig. 144) is transferred by convection and radiation to the surface of a stationary gaseous film which blankets the heating surface of the boiler. Or. perhaps, a coating of soot may interpose between the film of gas and the heating surface. The heat is then carried by conduction to the water in the boiler. It traverses the external film of gas, the coating of soot, the boiler plate, perhaps a layer of scale on the inner surface of the plate, and, finally, a film of stagnant water and steam before it passes into the mass of moving water in the boiler. During the progress of the heat flow from the outer surface of the external gaseous film to the moving water in the boiler, the mode of transfer alternates successively between external and internal (Sec. 112) conduction. When the heat is finally conducted into the moving water, the convection currents circulating therein distribute it throughout the mass.

Now, heat is not transferred as readily by external conduction as by internal conduction. Also, the rate of transfer by external conduction seems to vary, more or less, according to the various natures of the substances in contact. This introduces a factor that must be variously reckoned with where (Fig. 144) a series of dissimilar substances are successively in contact.

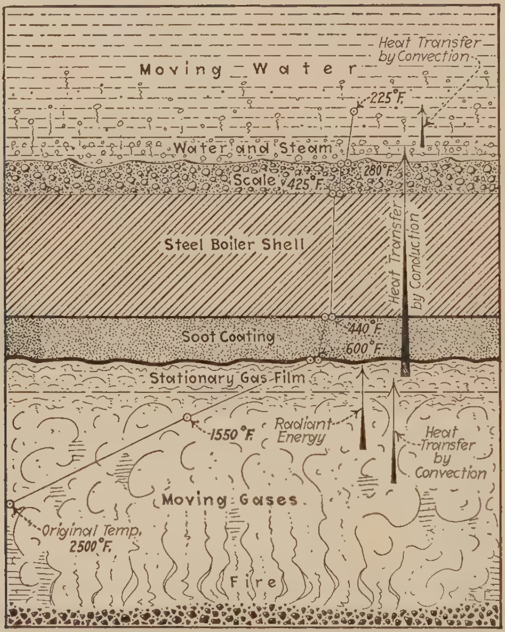


Fig. 144.—Diagrammatic representation of heat transfer in a boiler and furnace.

The rate of heat transfer by convection, both in the furnace and in the boiler, will be considerably modified by the velocity of flow of the furnace gases and of the water. As the velocity flow of either of these mediums increases, the thickness of the film of stagnant gas which blankets the heating surface externally, or of the film of stagnant water which adheres to the plate internally, will be materially diminished. These films are relatively poor conductors of heat.

It is evident, therefore, that the quantity of heat which may be transmitted, through the external film, from the convection currents in the furnace, and, through the internal film, to the convection currents in the boiler, will be greatly modified according to the thickness of the films.

The transfer of heat by radiation will, likewise (Sec. 143) be governed by variable conditions.

QUESTIONS ON DIVISION 5

1. What are the three modes of heat transfer?

2. State an instance wherein the three modes of heat transfer occur simultaneously.

3. What change in the motion of the molecules of a substance occurs when the substance is heated?

4. What is *heat conduction?* Give an example.

5. Why does the protruding end of a bar of iron remain cool while the other end is being heated in a forge fire?

6. What is *internal conduction? External conduction?* Give some examples of each.

7. What factors determine the flow of heat through a substance?

8. Explain the fundamental cause of the warmth which a blanket of snow secures to vegetable life.

9. In what ways do the elements of time and distance affect the rate of heat transfer between two points in any substance?

10. What is *thermal conductance?*

11. Why do not all materials conduct heat at the same rate?

12. What is the name of the unit of thermal conductance? Of thermal resistance? What is the value of each of these units?

13. What is *thermal conductivity?*

14. In what manner do temperature changes affect the thermal conductivities of substances?

15. What is *internal thermal resistance? External thermal resistance?*

16. What is *thermal resistivity?*

17. What should be the intrinsic properties, with respect to heat-effects, of the materials used in making an ice-box or a fireless cooker?

18. By what quantitative units are resistivity and conductivity expressed mathematically? Explain the meaning of each unit.

19. Explain the mutual relation existing between the British thermal unit and the units of conductivity and resistivity.

20. What is *convection?*

21. Explain the phenomena of convection in hot-water and hot-air heating systems and in ordinary stove heating.

22. Why are the tubes in horizontal water-tube boilers set sloping?

23. What is *radiation?*

24. Wherein does radiation chiefly differ from conduction and convection?

25. In what manner does the earth's atmosphere become heated by radiant energy from the sun?

26. What is *radiant energy?*

27. What is the velocity of radiant energy?

28. What characteristic must a substance possess in order that radiant energy may pass through it?

29. In what manner is a body heated by radiant energy?

30. Describe how radiant energy may be reflected.

31. Give some examples of refracted radiant energy.

32. What characteristic should a substance possess to render it a perfect absorber of radiant energy?

33. What kind of surface is best for radiating heat?

34. What material affords the closest approximation to the ideally perfect absorber of radiant energy?

35. What are the sources of radiant heat in the furnace of an externally fired boiler?

36. What circumstance generally limits the maximum temperature that may be realized in a boiler furnace?

37. In what manner does the velocity of the flow of gases in a boiler furnace chiefly affect the transfer of heat from the gases to the boiler?

PROBLEMS ON DIVISION 5

1. A body having a cross-sectional area of 5 sq. in. conducts 41 B.t.u. of heat per min. What would be the rate of heat conduction of a body of the same substance having a cross-section of 6.5 sq. in.?

2. If one end of an iron rod is heated to 500° F. in a forge fire, while the temperature of the opposite end is 100° F., what is the thermal pressure between the two ends?

3. The temperature of one end of a stone column is 300° F. The temperature of the opposite end is 70° F. The quantity of heat flowing, in 5 hr., between the two ends is 700 B.t.u. What is the conductance of the column?

4. A body has a conductance of 11 mohts. What thermal pressure will force 8,720 B.t.u. through the body in an hour and ten minutes?

5. The side sheets of the fire-box of a steel boiler are 0.5 in. thick. The area of each sheet is 30 sq. ft. What is the thermal conductance from the fire surface to the water surface of each sheet?

6. A steam pipe is covered with a 4-in. thickness of mineral wool. The length of the covering is 20 ft. Its mean diameter is 6 in. The temperature of the pipe is 300° F. The temperature of the surrounding air is 90° F. What quantity of heat flows, in 10 hr., through the covering?

7. A clean steel boiler tube has a thermal resistance of 0.000,267,2 thoms. If the average temperature on the fire side of the tube is 1,500° F., and on the water side 310° F., how much heat will flow through it in 5 hr.?

8. A brick wall is 9 in. thick. What is the thermal resistance through each square foot of its area?

9. The side wall of a brick boiler-setting is 6 ft. high, 15 ft. long and 15 in. thick. The average temperature on the furnace-face of the wall is 2,000° F., and on the outer face, 190° F. What is the heat-power loss through the wall?

10. The white-hot fuel in the fire-box of a locomotive-type boiler is at a temperature of 2,400° F. The crown-sheet temperature is 700° F. If the fire temperature is raised to 2,600° F., how much more heat per hour will the crown-sheet receive by radiation from the fire?

DIVISION 6

EFFECTS OF HEAT

153. The Three Possible Effects Of Adding Heat To A Substance Or Abstracting Heat From It were stated in Sec. 54, as (1) *Change of temperature.* (2) *Change of state.* (3) *External work.* In this division, it will be shown what changes in bodies may accompany these three fundamental effects of heat transfer. Some of these changes will then be treated more in detail in following divisions. In all cases, the aim shall be to discuss principally such changes as affect practical applications of heat, such as power plants, heating of buildings, refrigeration, and industrial systems generally.

NOTE.—THE ADDITION OR ABSTRACTION OF HEAT CHANGES THE "PROPERTIES" OF A SUBSTANCE AND THEREBY PERFORMS "PROCESSES."—A *property of a substance* is any characteristic of the substance which may be used to describe the substance or to describe what the substance is capable of doing—some properties are shape, size, density, temperature, state, taste, color, odor, solubility, strength, electric resistance, thermal resistance, chemical composition. A *process* is simply a change in one or more of the properties of a substance. In this division will be discussed some of the processes which accompany the addition of heat to or the abstraction of heat from substances. Also, since "change of temperature" is a process which frequently accompanies the addition or abstraction of heat, the influence of temperature on the other properties of substances will be discussed. The processes and properties which will be treated include: (1) *Expansion and contraction,* Secs. 159 and 160, also treated in detail by Div. 7. (2) *Melting,* Sec. 161, also treated in detail by Div. 9. (3) *Vaporization,* Sec. 162, also treated in detail by Div. 10. (4) *Sublimation,* Sec. 163. (5) *Chemical combination, decomposition, and dissociation,* Secs. 155 to 158. (6) *Viscosity,* Sec. 165. (7) *Absorption,* Sec. 168. (8) *Solution and solubility,* Secs. 168 to 174. (9) *Electric resistance,* Sec. 182. (10) *Strength,* Sec. 184. (11) *Capacity for emitting radiant energy,* Sec. 176.

154. A "Physical Process" is any change which a substance is made to undergo *without alternation of the arrangement of the atoms which compose its molecules.* Very frequently physical processes are the effects of heat addition or abstraction. Some examples of physical processes are: (1) *Change in temperature.* (2) *Change in volume.* (3) *Change in state*, as from solid to liquid or from liquid to gaseous. (4) *Absorption* (Sec. 168). (5) *Solution* (Sec. 170).

Note.—Physical Processes May Be "Reversible" Or "Irreversible" depending on whether, after a process is completed, the substance can be returned readily to its original condition. *Most physical processes are reversible.* Thus, water may readily be cooled after being heated or it may readily be condensed after being vaporized into steam. *Some physical processes are, however, irreversible.* Thus, if a 12-ft. board is cut into two 6-ft. lengths, it cannot again be made into a 12-ft. board.

155. A "Chemical Process" or Reaction is a change which a substance is made to undergo whereby its chemical composition (*the arrangement of the atoms in its molecules*) is altered. Chemical processes are, in general of four kinds: (1) *Combination*, wherein 2 or more substances combine to give 1 substance. (2) *Decomposition*, wherein 1 substance is changed into 2 or more substances. (3) *Displacement*, 1 element and 1 compound combine to give 1 other element and 1 other compound. (4) *Double decomposition*, wherein 2 compounds give 2 different compounds. Nearly all chemical processes are attended by the liberation or continual absorption of heat.

Examples.—If a strip of magnesium is lighted with a match, it takes fire and "burns" with a white flame. This (and every other) burning is actually a chemical combination of the material burned and oxygen from the air. If some mercuric oxide (red oxide of mercury) is heated in a test tube, globules of mercury will deposit on the cooler walls of the tube and oxygen (gas) will pass out of the tube—a lighted match placed in the mouth of the tube will glow in the oxygen. The mercuric oxide is "decomposed" into mercury and oxygen. If some bits of zinc are placed in a tube with some dilute hydrochloric (muriatic) acid, a gas will be evolved at the surface of the zinc. This gas will be found to burn with a pale blue flame—it is hydrogen. Here "displacement" occurs—the zinc (element) and the acid (compound) react to form hydrogen (element) and zinc chloride (compound). In the purification of water, a solution of lime (calcium hydroxide) and a solution of ferrous sulphate (copperas) are frequently introduced into the water which is to be purified. These two compounds, by "double decomposition," form ferrous hydroxide and calcium sulphate—the hydroxide forms into small flakes which slowly settle and carry with it the impurities which may be in the water. More examples of chemical reactions are given in succeeding sections.

Note.—The Distinction Between A "Chemical" And A "Physical" Process is this: Chemical processes have to do only with changes in the arrangement of the atoms within the molecules, whereas physical processes have to do only with changes exterior to the construction of the molecules. This distinction is important.

156. Dissociation Is A Reversible Decomposition.—Not all decompositions are reversible. If a piece of wood is heated in a closed vessel (so that no air can reach the wood), the piece will be decomposed, by the absorption of heat, into charcoal and some gases. The charcoal and the gases cannot, however, by man be made to re-combine to form wood. Hence, the decomposition of wood is *irreversible*. On the other hand, however, water can be decomposed (by an electric current or by heating to a very high temperature) into two gases, hydrogen and oxygen (Fig. 145). These gases will again combine, if mixed and ignited, to form water (Fig. 146). During the combination, as much

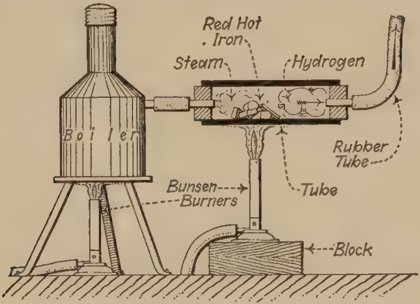


Fig. 145.—Decomposing water into hydrogen and oxygen—oxygen unites with hot iron forming iron oxide. Heat must be supplied, however, to maintain the decomposition. Hence, the heat is "absorbed" in the process.

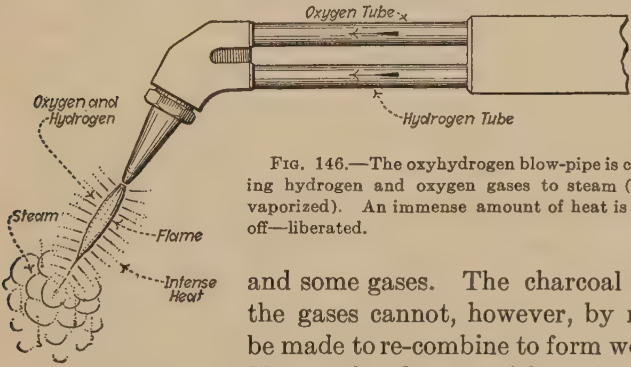


Fig. 146.—The oxyhydrogen blow-pipe is changing hydrogen and oxygen gases to steam (water vaporized). An immense amount of heat is given off—liberated.

heat is liberated as was absorbed when the water was decomposed. Hence, the decomposition of water is a *reversible chemical process*.

157. The Addition Of Heat Energy Is Necessary To Effect Certain Chemical Processes. However, Heat Energy Is Liberated By Most Chemical Processes.—As was explained in Sec. 28, energy of some sort is either required to effect or is liberated by every chemical process or reaction. It is the purpose here to give consideration to those chemical processes whereby only one kind of energy, *heat energy*, is either absorbed or liberated. Those chemical changes in which heat energy is liberated are called *exothermal processes*. Those in which heat energy is continuously absorbed are called *endothermal processes*. The amount of energy which is absorbed or liberated by the different chemical processes is usually determined initially by experiment; values are given in chemistry books and in handbooks such as the "Smithsonian Institute Tables." The amount of heat energy liberated or absorbed by a chemical reaction may in many cases, be determined with a calorimeter; see Sec. 456. The absorption or liberation of heat are not necessarily evidences of chemical processes. All physical processes are similarly accompanied by heat transfers. Examples are heating due to rubbing or percussion and the heat released or absorbed during changes of state (Sec. 54) of matter.

Explanation.—One pound of every substance (at a given temperature and under a given pressure) contains: (1) *A certain definite amount of chemical energy.* (2) *A certain definite amount of matter.* See Sec. 28. The amount of matter in the substance can be determined quite accurately by weighing. But there is no way in which the *total* amount of chemical energy in it can be determined. This chemical energy was imparted to the atoms of the substance both when they were first evolved and possibly, also at later times, whenever the atoms were parties to chemical reactions. Thus chemical energy, of an unknown amount, normally resides "bound in" or latent in every substance.

However, if a chemical process occurs whereby the molecules of given weights of two or more substances are disrupted into their constituent atoms which atoms then recombine to form the molecules of a new substance or substances, *a definite amount of energy is either absorbed or released* during the process. The amount of heat energy (in, say, British thermal units) which will be absorbed or released by any chemical reaction between given weights of two or more substances must, apparently, be determined by experiment; there seems to be no way, except in certain special cases, to compute it. In most cases, the energy is thus absorbed or liberated as heat energy. If heat energy is absorbed, it is automatically transformed into chemical energy which then resides latent within the new substance or substances. If heat energy is liberated, it is energy which was transformed from part of the chemical energy which formerly resided—latent—within the original substances. Examples of the amounts of heat energy thus absorbed or liberated by certain chemical reactions are given below.

Hence, it is evident that if heat energy is liberated by a chemical reaction, this energy is part of the store, of unknown amount, of chemical energy which formerly resided within the molecules of the substances. Possibly a part of the liberated heat is derived from each of the original substances which were parties in the reaction. If heat energy is absorbed by a chemical reaction, the energy thus added goes to increase the store of chemical energy in the molecules of the resulting substance or substances. Somehow or other, chemical energy is necessary to "hold" the atoms in the molecules, different amounts of it being necessary for different kinds of atoms and molecules. So when the molecular structure—the substance—is changed, the chemical energy must be either released or absorbed.

When a compound is decomposed into its constituent elements, the amount of heat absorbed or liberated is exactly the same as that which was evolved or absorbed in the original formation of the compound. When both combination and decomposition are involved in a complex chemical change, the heat liberated or absorbed is the net result of the two reactions.

EXAMPLE.—When water is decomposed, see equations below (Fig. 145), by any process whatsoever, into oxygen and hydrogen, heat energy is absorbed. When oxygen and hydrogen combine (Fig. 146), as in combustion, much heat energy is liberated.

158. Thermochemical Equations are equations which show not only the chemical reaction of a process but which also show the amount of heat absorbed on liberated by the process; examples follow. The subject can be considered only very briefly here; for further information see some good modern textbook on chemistry. In the following equations, which are merely the records of many experiments, each symbol stands for a chemical element thus: C = carbon. O = oxygen. Cl = chlorine. Now a chemical equation is:

$$C + O_2 = CO_2 \tag{84}$$

which means that 1 atom of carbon, a solid, will combine with

2 atoms of oxygen, a gas, to form one molecule of carbon dioxide gas. A corresponding thermochemical equation is:

(85) $1\ lb.\ C + 2\frac{2}{3}\ lb.\ O = 3\frac{2}{3}\ lb.\ CO_2 + 14{,}650\ B.t.u.$

which means that 1 lb. of carbon will combine with $2\frac{2}{3}$ lb. of oxygen gas and form $3\frac{2}{3}$ lb. of carbon dioxide gas and furthermore that during this process 14,650 B.t.u. of heat energy will be liberated. If 2 lb. of carbon combined with $5\frac{1}{3}$ lb. of oxygen the result would be $7\frac{1}{3}$ lb. of carbon dioxide gas and the liberation of 29,300 B.t.u., and so on. The chemistry books show that an atom of oxygen weighs $1\frac{1}{3}$ times as much as an atom of carbon. This means that (since two atoms of oxygen will combine with one atom of carbon) the weight of oxygen necessary in For. (85) will be: $2 \times 1\frac{1}{3} = 2\frac{2}{3}$ times the weight of carbon required. Note that the weight of the resulting substance "$3\frac{2}{3}$ lb. of CO_2" is the sum of the weights of the two original substances. The energy, obviously, has no weight. Fors. (84) and (85) are very important to the steam engineer since they show the underlying reaction for the chemical process of the combustion or burning of fuels. Combustion is further discussed in Div. 14, which see.

Examples of other chemical and thermochemical formulas are:

(86) $$2H_2O = 2H_2 + O_2$$

which means that 2 molecules of water (H_2O), each composed of 2 atoms of hydrogen and 1 atom of oxygen can be decomposed into 4 atoms of hydrogen, a gas, and 2 atoms of oxygen, a gas. A corresponding thermochemical equation is:

(87) $$9\ lb.\ H_2O = 1\ lb.\ H + 8\ lb.\ O - 62{,}100\ B.t.u.$$

which means that 9 lb. of water when chemically decomposed will furnish 1 lb. of hydrogen gas, 8 lb. of oxygen gas and, in addition, that 62,100 B.t.u. of energy must be supplied to effect the decomposition. The minus sign (−) preceding the "62,100" means that this amount of heat energy must be added. A plus sign (+) in the same position means that energy will be liberated during the reaction. That is:

(88) $$2H_2 + O_2 = 2H_2O$$

or stating the corresponding thermochemical equation:

(89) $$1\ lb.\ H + 8\ lb.\ O = 9\ lb.\ H_2O + 62{,}100\ B.t.u.$$

which means that if 1 lb. of hydrogen and 8 lb. of oxygen are combined to form 9 lb. of water, 62,100 B.t.u. will be liberated by the reaction. Note that For. (89) is the reverse of For. (87).

Note.—The Rate At Which A Given Chemical Process Is Allowed To Proceed Has No Influence On The Total Amount Of Heat Absorbed Or Liberated Thereby.—Thus, a piece of iron may be permitted to "burn" slowly by rusting away in many months by combining with the oxygen of the air. Or instead it may be permitted to burn away very rapidly—in a fraction of a minute—in pure oxygen gas. But in each case the total amount of heat liberated by the combination of the iron with the oxygen will be the same.

159. "Expansion" Is An Effect Of Increased Molecular Motion in a body of matter. (See Div. 7 for extended discussion.) When the temperature of a body is increased, it expands or increases in size, for the following reason: The molecules of a substance (Sec. 46) are not in actual contact. They are in motion, constantly *vibrating*—hitting one another and rebounding. When their vibratory motion is increased—when the temperature increases—they bounce further away from one another. Thus, there is a tendency to increase the average distance between the molecules. The cumulative effect is an expansion of the whole mass of the substance which they form. But addition of heat is the real cause of the phenomena, since molecular vibration (Sec. 52) is heat. However, addition of heat does not always (Sec. 54 and 187) cause a temperature increase and expansion.

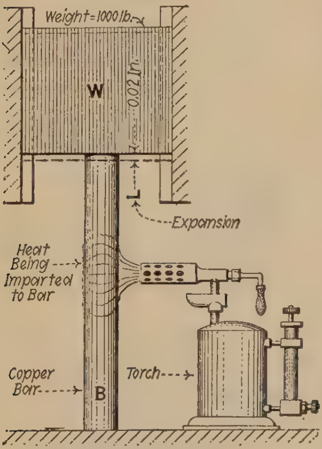


Fig. 147.—Work done by expansion.

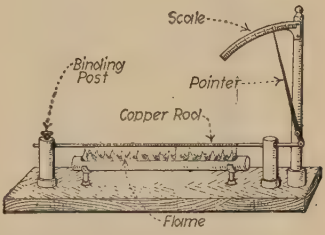


Fig. 148.—Addition of heat expands metals.

Example.—A bar of copper (*B*, Figs. 147 and 148) is longer when hot than when cold.

160. "Contraction" Is An Effect Of Decreased Molecular Motion In A Body Of Matter.—It is the reverse (Sec. 159) of expansion. Contraction is manifested by a decrease in the size of the body. When the temperature of a body decreases it contracts. The decrease of temperature of a substance consists, essentially, in a diminishment of the vibration of the molecules of the substance. As the vibratory motion of the molecules diminishes. the average distance between them (Sec. 52) likewise diminishes. The cumulative effect is a contraction of the entire body of matter which the molecules form.

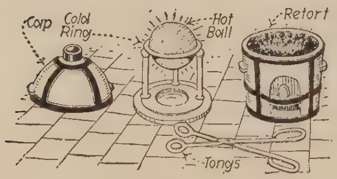


Fig. 149.—The ball will pass through the ring when the ball is cold but will not pass through when it is hot.

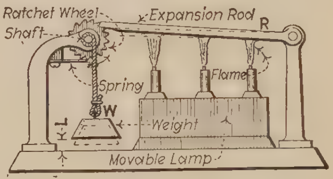


Fig. 150.—Raising a weight by heating and cooling a rod.

Examples.—See Fig. 149. Also, a steel collar may be bored to a slightly smaller internal diameter than the outside diameter of a steel shaft. Thus it will be impossible to slip the collar over the shaft when both are at normal temperature. But the collar may be heated. The accompanying expansion will then enlarge its bore until it can be readily slipped over the shaft. If it is then permitted to cool to the temperature

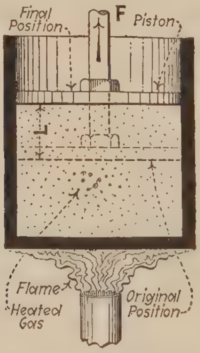


Fig. 151.—Work done by expansion of gas.

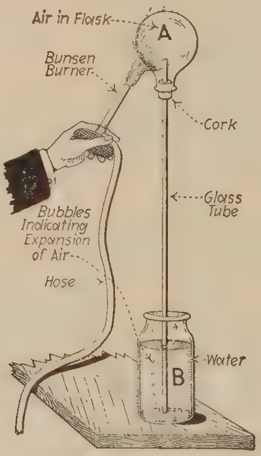


Fig. 152.—Addition of heat causes the air to expand and thus increases its volume.

of the shaft, the collar will gradually contract and will finally grip the shaft so tightly as to be immovable.

NOTE.—EXTERNAL WORK MAY BE PERFORMED, THROUGH THE EXPANSION AND CONTRACTION OF MATERIALS, BY DIRECT APPLICATIONS OF HEAT.—A copper bar (Fig. 147) is heated by the flame of a blow-torch. The bar is thereby expanded and lifts a block, of **W** lb. weight, a distance of **L** in. The external work performed by the applied heat, in lifting the block, may, therefore, be expressed as **WL** in.-lb. = 1,000 × 0.02 = 20 *in.-lb.* By alternately heating and cooling the rod *R* (Fig. 150) the ratchet-wheel could be rotated. External work in raising the weight **W**, might thus be performed by the heat energy transferred from the flame to the bar.

Applying heat to a confined gas (Fig. 151) increases the volume of the gas. The gas expands and raises the piston. Thus the heat energy which is transferred from the applied flame is, through the expansion of the gas transmitted into external mechanical work. In Fig. 152, the addition of heat to the air in *A* expands the air, as is shown by the bubbles coming out of the water in *B*, thus external work is done in forcing out the air globules against the force of atmospheric pressure.

161. "Melting" Or "Fusion" Is The Transition Of A Substance From The Solid To The Liquid State.

(Fig. 153.) There is, for practically every solid, a certain temperature at which that solid will melt. This temperature is called the *melting-point* or the *fusing-point* of the substance. See Table 285. Furthermore, heat (positive disgregation heat, Sec. 103) is always required to effect the change from solid to liquid form. Thus, melting is an effect of heat addition. This subject is discussed fully in Div. 9.

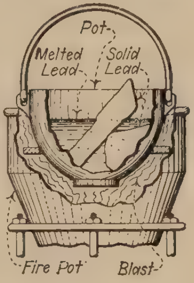


FIG. 153.—Melting lead.

NOTE.—"SOLIDIFICATION" IS THE OPPOSITE OF "MELTING." It is the transition of a substance from the liquid to the solid state. Heat (negative disgregation heat) must be given up by it when a body solidifies. Hence solidification is an effect of heat abstraction.

162. "Vaporization" Is The Transition Of A Substance From The Liquid State To The Vapor Form Of The Gaseous State

(Figs. 154 and 155). In general, there is a certain temperature (depending on the pressure on the liquid) for each substance at which that substance vaporizes. This temperature is commonly called the *point of vaporization* or *boiling* *point* of the particular substance. Furthermore, heat (positive disgregation heat, Sec. 104) must always be added to it to change a substance from the liquid to the gaseous state. Hence, vaporization is an effect of heat. This subject is fully discussed in Div. 10.

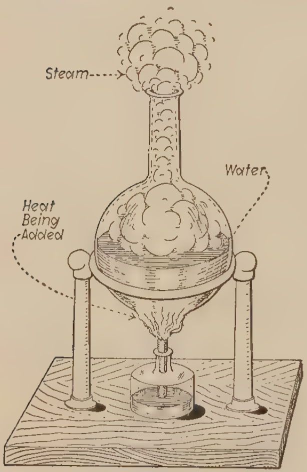


Fig. 154.—Vaporization is the transition from a liquid to a gaseous condition.

Note.—"Liquefaction" Or "Condensation" Is The Opposite Of Vaporization.—It is the transition of a substance from the vapor form of the gaseous state to the liquid state. (In general parlance "condensation" means the reduction of a vapor or gas to the liquid or solid state or of a liquid to a solid or semi-solid state. But in technical usage the term is usually now employed to imply only "the reduction of a vapor to the liquid state.") Heat—negative disgregation heat—must be given up by it when a vapor liquefies. Hence, liquefaction is an effect of heat abstraction.

Note.—Melting And Vaporization Are Called Constant-temperature Processes because the heat required to effect them is expended in disgregation work (Sec. 98) and not in vibration work (Sec. 97) which would raise the temperature.

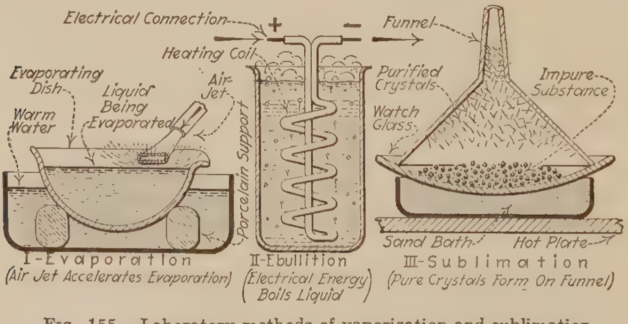


Fig. 155.—Laboratory methods of vaporization and sublimation.

When a block of ice melts to water, the temperature of the resulting water will (Sec. 96) be that of the original block of ice. A great quantity of heat—positive disgregation heat— has, nevertheless, been absorbed in this process of fusion. Conversely, when a liquid substance solidifies, negative disgregation heat is given up by it.

Water may be converted to steam (Fig. 156) without a change of temperature (Sec. 96). Or steam may be condensed to water (Fig. 157) (Sec. 329) without a change of temperature. In the first instance, however, the process can be consummated only by addition of a relatively-great quantity of "positive" disgregation heat and in the second instance only by a corresponding subtraction of "negative" disgregation heat.

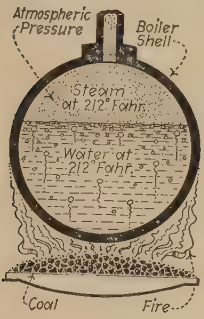


Fig. 156.—Change from liquid to gas with temperature constant but with addition of heat. This process may be reversed.

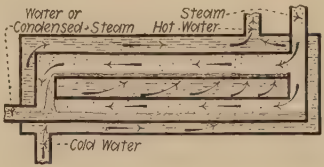


Fig. 157.—The condenser. The heat added to water in the boilers to convert it to steam is given up in the condenser to the cooling water. Thereby, the steam is reconverted into water.

163. Sublimation Is The Direct Transition Of A Substance Which Is In The Solid State To Its Vapor Form Of The Gaseous State, without its, apparently, passing through the liquid state. All solid substances sublime (theoretically at least) at any temperature. The process is somewhat similar to, but not the same as, vaporization; see explanation below. In general, sublimation is a very much slower process than is vaporization. Obviously, sublimation can occur only at temperatures below the freezing point—or melting point. Thus the molecules of a solid substance are found in the vaporous condition above the surface of a solid as well as above that of a liquid. Sublimation is of minor practical importance in power-plant work but is widely used in the chemical industry as a method of purification.

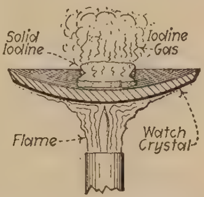


Fig. 158.—Some solids may change to gas without becoming liquid.

Examples.—Snow And Ice Will Sublime even though the temperature of the surrounding air is considerably below the freezing point—so low that the snow or ice can not melt. Damp clothing, which have been hung on a line out-of-doors and then frozen, will become dry in a freezing temperature. If a piece of solid iodine (Fig. 158) is placed on a watch crystal, and heat is applied, the iodine will sublime directly into a vapor. It will not, apparently, undergo a preliminary liquefaction. The odor of camphor will, due to the sublimation of the camphor, be quickly recognized, some distance away, if a quantity of camphor gum be exposed in a current of air. In general, odors of all sorts, from solid bodies, are evidences of sublimation.

Explanation Of Sublimation.—A molecule which is very near the surface of a solid body may bounce entirely out of it (Fig. 287) without colliding with others. Since such an escaping molecule is already moving at an extremely high velocity, it continues in its now unobstructed path. Soon, it flies so far away from the body that the remaining molecules (in the solid substance) exert no attractive force on the insurgent. The molecule, now being free of the restraints which were imposed on it in the solid, becomes a gas or vapor molecule.

164. The "Heat Of Sublimation," sometimes also called *the latent heat of sublimation*, is the amount of heat—usually expressed in British thermal units—required to sublime, or to convert into a vapor, a unit weight—usually 1 lb.—of the solid. The heat of sublimation can be conveniently calculated as the difference between the heat content of the solid and that of the vapor. At the *triple point* for the substance (which is that temperature and pressure at which a substance can exist in either the solid, the liquid, or the gaseous state) it is true that:

$$\text{(90)} \quad \textit{Heat of sublimation} = (\textit{Latent heat of fusion}) + (\textit{Latent heat of vaporization})$$

The above For. (90) will also hold quite closely for any temperature of the solid near the triple-point temperature. More accurately, for any given temperature of the solid, the heat of sublimation is (very closely) the same as the net amount of heat that is necessary to: (1) *Warm the solid to its melting point.* (2) *Melt the solid.* (3) *Vaporize the resulting liquid.* (4) *Decrease the temperature of the resulting vapor from that of the vaporization to the given temperature* at a constant quality of 100 per cent. This heat to *decrease* the temperature is a substraction—not an addition.

Example.—At 32° F., the latent heat of vaporization for water is 1,073.4 B.t.u. per lb., as is shown by steam Table 394. The latent heat of fusion of ice, from Table 291 is 143.33. What is the heat of sublimation of ice at this temperature? Solution.—Substituting in For. (90): *Heat of sublimation* = (*Latent heat of fusion*) + (*Latent heat of vaporization*) = 143.3 + 1,073.4 = 1,216.7 *B.t.u. per lb.*

165. Viscosity Is The Internal Friction Of Liquid, Semi-liquid, Or Plastic Substances.—It occurs as the molecules flow by one another. Every substance possesses this internal friction in some degree. Practically all solid substances, acquire, when heated, a tendency to flow. That is, their viscosities decrease as their temperatures increase; they become liquid, semi-liquid, or more or less plastic. The viscosities increase as the temperatures diminish. Thus a change of viscosity is an effect of heat.

NOTE.—THE FLOWING TENDENCY—THE DIFFERENCE IN VISCOSITY—OF SUBSTANCES IS, OBVIOUSLY, THE CHIEF DIFFERENCE, BETWEEN SOLIDS AND FLUIDS. Is is commonly assumed that: *A fluid is any substance that exhibits a definite flow to ordinary observation.* By this definition, both the molten iron gushing freely from the tap-hole of a foundry cupola, and the stream of thick slag rolling ponderously and sluggishly from the slag-hole, are fluids. Likewise, this definition of a fluid includes all gaseous substances. However, the definition eliminates from consideration all apparently plastic substances, as masses of beeswax, moist putty, building mortar, and the like.

EXAMPLES.—A wax candle (Fig. 159), whether held horizontally or vertically, will ultimately bend under its own weight in a warm room; it is highly viscous. A mass of relatively cold pitch, apparently hard, is likewise susceptible to changes of shape, due to its own weight. Bodies of other viscous substances such as molasses, honey, tar, oil and similar substances, undergo changes of shape somewhat in the manner of true liquids, as water, though less rapidly. A mass of solid lead, at normal temperature, will flow when subjected to pressure.

166. The Viscosity Of A Substance Varies With Its Temperature.—The higher the temperature the less the viscosity. The wax of a candle (Fig. 159) is, normally, quite viscous. It may, however, be readily heated to a temperature that will vastly diminish its viscosity. Under a very high temperature the wax will become extremely thin and fluid. The viscosity of lubricating oils likewise varies, though to a far less extent, as the temperature varies. The quantitative effect of temperature on viscosity varies with the different materials.

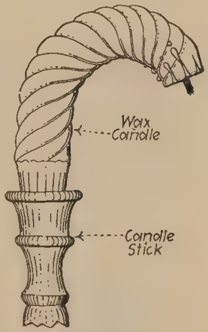


FIG. 159.—A wax candle becomes soft in a warm room.

Note.—Mobility Is, In A Sense, The Opposite Of Viscosity.—A very thin liquid, that pours readily and splashes freely, is said to possess *mobility*.

167. The Specific Viscosity Of A Liquid is the ratio of the time consumed by a certain volume of the liquid (Fig. 160), at 60° F., in flowing through an orifice, to the time consumed by an equal volume of distilled water in flowing, under the same conditions, through an orifice of the same dimensions. The quantity of the liquid is usually taken as 50 c.c. (cubic centimeters).

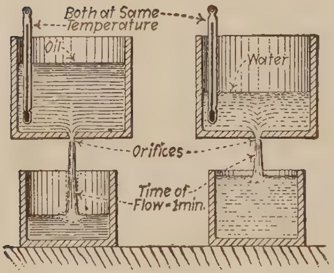


Fig. 160.—Showing difference in viscosity of oil and water.

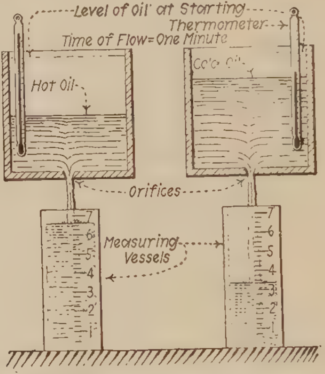


Fig. 161.—Showing difference in viscosity of hot and cold material.

Note.—The Temperature In Viscosity Tests is often taken at other than 60° F. It may be 120° F. For many purposes, 212° F. may be a convenient test temperature. When a lubricating oil is intended for an engine cylinder using superheated steam, or for an internal-combustion engine, the test temperature is correspondingly high. It is important that viscosity tests of lubricating oils (Fig. 161) be made at the temperatures under which the oils are to be used.

168. Many Solid Substances Possess The Property Of Absorbing Or Liberating Gaseous Substances.—Temperature—the degree of heat—is often a determining factor in these phenomena. A solids' capacity for absorbing a gas is generally less when the solid is hot than when it is cold. Heat is often liberated by the absorption of a gas by a solid.

Examples.—A fine platinum wire, held in a mixture of hydrogen and oxygen gases will absorb the oxygen verv rapidly. The wire will, spontaneously become heated to incandescense and will finally ignite the surrounding gas; see explanation below. Endeavors have been made to utilize this principle (Figs. 162 and 163) in the making of gas-lighters.

A quantity of wood charcoal (Fig. 164) will absorb a quantity of gas which, normally, may occupy many times the volume of the charcoal. Boxwood charcoal will absorb a volume of ammonia equal to 90 times its own volume. Likewise, it will absorb 35 times its own volume of carbon dioxide.

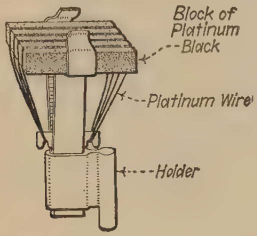


FIG. 162.—A gas lighter. Platinum black glows due to gas absorption. Platinum wire is thereby heated, becomes incandescent and lights gas.

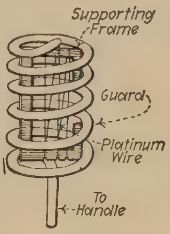


FIG. 163.—A platinum-wire gas igniter.

EXPLANATION.—It is claimed that all solid substances will, at their surfaces, exert an attraction on the molecules of gases with which they are in contact and that this attraction is of such a nature that a more or less thick layer of the gas is condensed on the surface of the solid. Thus, solids such as charcoal, which because of its porous structure exhibits a large external surface, will "absorb" more gas than structurally dense solids. The attractions of the molecules of different solids and different gases are not the same. Freshly made dogwood charcoal (used in making the best gunpowder), when pulverized immediately after its preparation, often takes fire spontaneously on account of the heat liberation which accompanies the condensation on its surfaces of oxygen from the air. Likewise, when platinum in a finely divided state known as *platinum black* (Fig. 162) is placed in a mixture of oxygen and hydrogen, the oxygen rapidly condenses on its surface and gives up its latent heat of vaporization (Sec. 322). This raises the temperature of the surrounding particles of gas to the point where they combine slowly. This slow burning, however, gives off much heat to the surrounding particles. Hence, the temperature of the gaseous mixture quickly reaches a value which explodes the mixture.

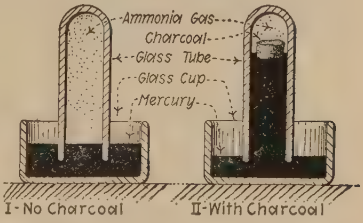


FIG. 164.—Illustrating absorption of a gas by a solid.

Note.—The Gas-absorptive Property Of Charcoal Renders It Valuable For Counteracting The Noxious Effects Of Gases Resulting From Animal And Vegetable Decay.—It is commonly used for clarifying the air in the holds of sea-going vessels, and in tunnels. Charcoal made from nut shells is extensively used in gas masks for absorbing poisonous gases.

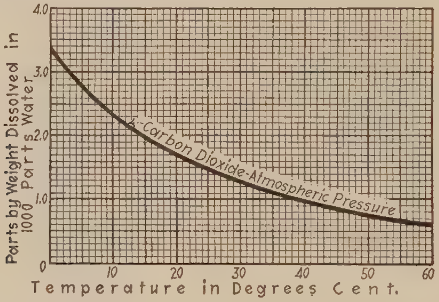


Fig. 165.—Showing variation of solubility of carbon dioxide in water with variation of temperatures. (Plotted from Smithsonian Tables.)

169. Liquid Substances Possess The Property Of Absorbing Or Liberating Gaseous Substances.

—A liquid will generally absorb (Fig. 165) more gas when it is cool than when it is hot.

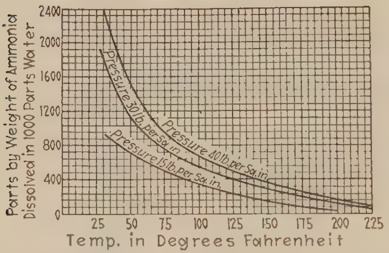


Fig. 166.—Showing effect of heat on the amount of ammonia gas held in a water solution. (Plotted from values in Mark's "Mechanical Engineers' Handbook.")

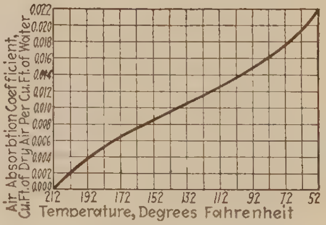


Fig. 167.—Air absorption of water at various temperatures.

Examples.—Ammonia gas is readily absorbed (Fig. 166) by cool water. The resultant mixture is known, commercially, as aqua ammonia (ammonia water). Boiling will expel the gas from a mass of aqua ammonia. These principles are utilized (Sec. 637) in the operation of absorption refrigerating systems. Water (Fig. 167) is always impregnated, more or less, with air. Slow heating of a quantity of cool water (Fig. 168) causes small bubbles to appear. These are due to release of air from the liquid. Fish breath air from the water in which they live.

Note.—Pre-expulsion Of Oxygen And Other Gases From The Boiler Feed Water In Power Plants Is Often Necessary.—Such gases might otherwise become distilled from the water after it enters the boilers. Thus they would be rendered free to form corrosive acids within the boilers. By preheating the feed-water (Fig. 169) much deleterious gas may be driven off.

170. Many Solids Are Soluble In Liquids.—If a small permanganate-of-potash crystal is dropped into a vessel of water, the adjacent water will, immediately, become colored. By degrees, all of the water will become colored. The crystal has *dissolved* in the water. Similarly, if sugar crystals be placed in a tumbler of water, they will dissolve therein. The water will become sweet. Heat is usually liberated or absorbed while a solid goes into solution in a liquid. Hence, *solution is an effect of heat.*

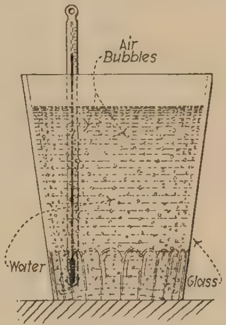


Fig. 168.—If a glass of cold water is placed in the sun's rays on a hot day and allowed to stand until warm, small air bubbles will cling to surface of glass. Air was in solution.

Examples.—Water is a solvent for a greater number of different solids than any other known liquid. Alcohol is a solvent for some solids for which water is not. Thus, resin and shellac dissolve readily in alcohol but not at all in water. Most greases are soluble in benzine. Beeswax is soluble only in turpentine. Sulphur is soluble in carbon bisulphide.

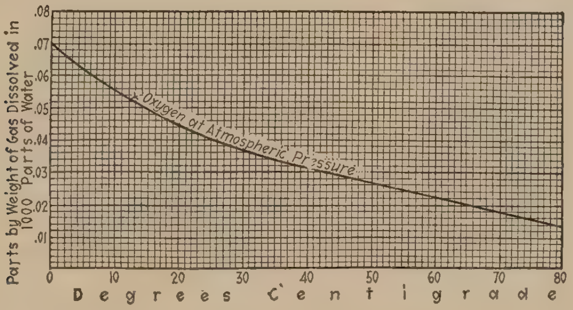


Fig. 169.—Showing effect of heat on amount of oxygen held in a water solution.

171. The Quantity Of A Solid Which A Given Liquid Will Dissolve Is Determined By The Nature Of The Substances And Their Temperatures (Fig. 170). Water will dissolve about three times as much table salt as will alcohol. When a liquid, at a certain temperature, has dissolved all of a certain solid which it will absorb, it will, generally, dissolve more

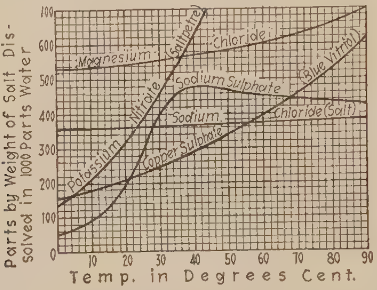


Fig. 170.—Showing the effect of heat on the solubility of various salts in water. (From Smithsonian Physical Table.)

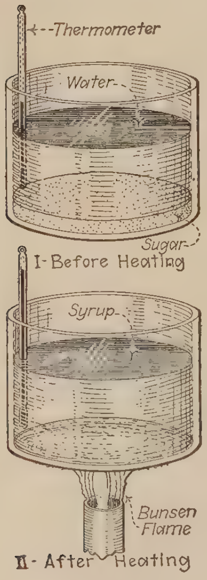


Fig. 171.—A hot liquid usually dissolves more of a solid than will a cold one.

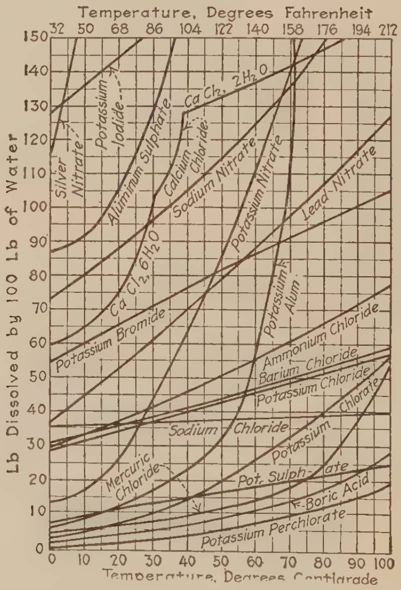


Fig. 172.—Graphs showing variation with temperature of the solubility of various substances in water. (Alex Smith, "College Chemistry.")

(although sometimes less) of the solid if the temperature of the liquid is increased (Fig. 171). The effect of variations in temperature on the solubility of various solids in water is shown graphically in Fig. 172. It will be noted that common salt (sodium chloride) has an almost constant solubility. The rate of dissolving of salt is, of course, much greater at a higher temperature. Also, the rate of dissolution (rapidity of dissolving) may usually be increased considerably by raising the temperature.

Note.—A Saturated Solution exists when a liquid has dissolved all of a substance which it will absorb from the solid form at that temperature. The solution is then said to be *saturated.*

172. Dissolving Solids In Liquids Often Causes A Temperature Change.—When there is a temperature change there is usually a volume change also. That is, the solution will occupy a different volume from the sum of the volumes of the solid and original liquid. Sometimes heat is absorbed; sometimes it is given off. The volume of the solution may be greater or less than the sum of the volumes of the solid and original liquid. Some substances dissolve or unite with water with the liberation of much heat. When this occurs, a well-defined chemical reaction has usually occurred.

173. The Vapor Issuing From A Hot Solution Is, Generally, Free From Solid Matter.—The solids are left in solution in the containing vessel. Hence, if all of the liquid content of a solution is boiled away, the total solid portion may thereby be recovered. This phenomena is of considerable importance in power-plant operation. The solids which are carried in solution in the boiler feed water are deposited on the interior of the boiler shell as the water is evaporated and passes away as steam. Similar solid-matter deposits occur in condensers. A somewhat similar phenomena is distillation, (Sec. 345).

Note.—Some Solids Are Held More Readily In Cold-water Solutions Than Hot-water Solutions.—This is an additional cause of solid-matter deposits in steam-generating vessels. Thus, natural waters frequently contain calcium bicarbonate which, when heated to about 212° F., decomposes giving calcium carbonate, a relatively insoluble substance. The calcium carbonate collects on the interior surfaces of the vessel forming a spongy solid mass. Another salt, calcium sulphate, comes less soluble when heated to about 300° F. than when cold. If, due to evaporation, a solution becomes concentrated with calcium sulphate, this salt will settle as a hard, porcelain-like coating inside the boiler—it is very difficult to remove and offers great resistance to the passage of heat through it.

174. "Scale" Is The Hard Substance Which Forms On The Interior Surfaces Of Boilers And Power-plant Auxiliaries Which Carry Hot Water.—Scale is formed (Sec. 345) by precipitation and hardening of the solids (salts) carried in the cold, or relatively cold, feed water. Scale is usually formed from "hard" water. *Hard water* may be defined as water which contains in solution mineral compounds that curdle or precipitate soap when soap is added to the water.

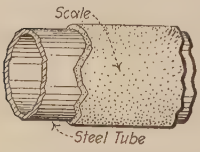


Fig. 173.—Section of tube from fire-tube boiler showing deposit of scale around it—due to heat.

Important among the many scale-forming solids found in boiler-feed and condensing waters are *calcium sulphate, calcium carbonate, magnesium sulphate, and magnesium carbonate.*

Note.—When Successive Increments Of The Above Specified Solids Are Precipitated in a containing vessel, as a steam boiler, they become cemented (Fig. 173), by absorption of heat from the heating surfaces, into a solid and more or less hard coating of scale. Such scale clings tenaciously to the metal surfaces. Since scale is a very poor conductor of heat, it affects economy very adversely. This subject is further treated in the author's Steam Boilers.

175. Heat Energy May Be Transformed Directly Into Electrical Energy.—When two dissimilar metals, as antimony and bismuth, are placed in contact, an electromotive force develops at their junction. If the two metals be connected to form a closed circuit (all parts of the circuit being at the same temperature), electromotive forces will also be produced at the other junctions of dissimilar metals and the sum of all electromotive forces in the circuit will be zero—hence no current will flow in the circuit. But if one junction of the dissimilar metals is heated, as in Fig. 174, a decidedly larger electromotive force will be developed at that junction. A current will then flow in the circuit.

Note.—Except In The Construction Of Pyrometers (Fig. 175) There Are Few Practical Applications Of The Electrical Effect

Of Heat.—The current flowing (Fig. 175) is an indication of the difference in temperature between the hot joint, H, and the cold joint, C. If a sufficient number of thermo-couple cells (Fig. 174) be connected in series, the resulting battery will furnish enough energy to heat, to incandescence, the filament of a small electric lamp.

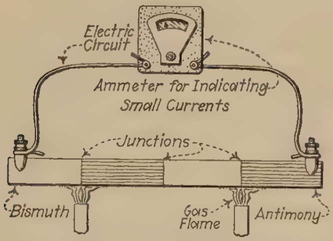


Fig. 174.—The thermopile.

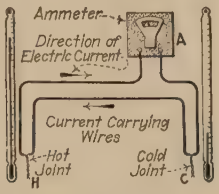


Fig. 175.—Principle of the thermo-couple electric pyrometer for measuring high temperatures.

176. Light May Be Regarded As An Effect Of Heat.—It is the visible criterion of radiant energy (Sec. 31). Hence, since radiant energy is emitted only by hot bodies, heat may be considered as a fundamental source of light. Light waves can be shown to also carry radiant heat. This may be shown by causing the light to impinge upon surfaces which possess certain qualities. A black surface is the best absorber of light. A black surface is always found to absorb heat as it absorbs light.

177. "Radiant Energy" Is A Vibratory Motion In The Æther.—When an object is heated, the molecules which compose it are made to vibrate more rapidly. These particles, being in contact with the æther, set it in motion. Thus, the vibrations are transmitted away from the object as radiant energy. Heat which is transmitted by radiation is radiant heat. See Sec. 138 for a further discussion of this subject.

Examples.—The heat which reaches the earth from the sun is radiant heat. A hot stove will radiate heat. The radiant heat from the sun will warm the interior of a greenhouse, even when the outside air is cold. This proves that the sun's radiant heat is transmitted through the æther rather than through the air. Radiant energy (light or heat) will cause a *radiometer* (Fig. 176) to rotate.

178. Radiant Energy May Be Said To Be Visible Or Invisible according to the length of its wave in the æther. Waves in the æther may be thought of as similar to the waves which travel along the surface of a pool of quiet water when a pebble is dropped into it. The *wave length* (see Table 19) is the distance from the crest of one wave to the crest of the next. Æther waves have different wave lengths. Waves of lengths from about 1/64,000 in. to 1/32,000 in. act upon the nerves of the eye and thereby produce the sensation of sight. Such are called *light waves*. *Heat waves* are *longer* than light waves varying in length from about 1/32,000 in. to 1/7,000 in.

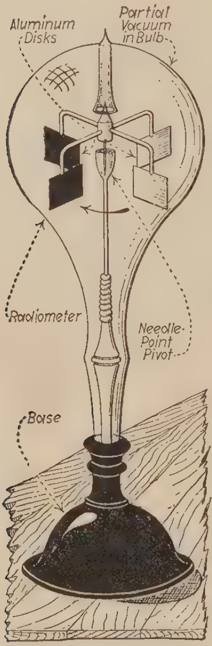


Fig. 176.—Light from the sun or even from a candle will cause the radiometer to rotate. The aluminum vanes are coated on one side with lamp black which is a good absorber of radiant energy. If only a slight vacuum exists in the bulb, the vanes will so rotate that the blackened sides move toward the light. The explanation of this action is: The black faces absorb radiant energy and are heated thereby. The air immediately adjacent to these black faces is also heated. The heated air rises by convection and thus causes a slightly smaller pressure on the black face of a vane than on its bright face. This slight difference of pressure causes rotation. But if the bulb is very well exhausted, its rotation will be such that the blackened faces move away from the light. The explanation of this action is too lengthy to be given here; the reader is referred to a good textbook on physics.

Note.—Waves Shorter Than 1/64,000 In. Do Not Affect The Eye-nerves, hence they are invisible. But some of these short waves will cause certain chemical actions—they will cause reactions in the coating on a photographic plate. These invisible short waves are called ultra-violet waves.

Note.—Light-, Heat- and Electric-waves Are All Æther Waves and All Travel At The Same Speed, which is about 186,000 mi. per sec. But they differ in wave length, that is, in frequency. Electrical, or wireless-telegraph and telephone waves are much longer (they may be several miles long) than heat-waves. However, they possess the same general characteristics. Herein is evidenced the close connection between—or possibly the fundamental identity of—light, heat, and electricity. See the Author's Practical Electric Illumination for a further and detailed explanation of the transmission of radiant energy through the æther.

179. Table Showing The Wave Lengths Of Radiant Energy.—Waves shorter, even than those here listed are radiated in the form of X- and gamma rays. (From the SMITHSONIAN TABLES.)

Visibility	Kind of wave	Wave length		Number of waves per inch	Frequency in cycles per second
		Centimeters	Inches		
Too short to be visible........	Shortest ultra-violet........	0.000,006	0.000,002	420,000.	5,900,000,000,000,000
Visible	Shortest visible (violet).....	0.000,036	0.000,014	69,000.	840,000,000,000,000
	Violet, longest............	0.000,045	0.000,017	56,000.	690,000,000,000,000
	Blue, shortest............	0.000,045	0.000,017	56,000.	690,000,000,000,000
	Blue, longest.............	0.000,049	0.000,019	52,000.	620,000,000,000,000
	Green, shortest...........	0.000,049	0.000,019	52,000.	620,000,000,000,000
	Green, longest............	0.000,055	0.000,021	46,000.	560,000,000,000,000
	Yellow, shortest..........	0.000,055	0.000,021	46,000.	560,000,000,000,000
	Yellow, longest...........	0.000,059	0.000,023	43,000.	510,000.000,000,000
	Orange, shortest..........	0.000,059	0.000,023	43,000.	510,000,000,000,000
	Orange, longest...........	0.000,065	0.000,026	39,000.	450,000,000,000,000
	Red, shortest.............	0.000,065	0.000,026	39,000.	450,000,000,000,000
	Red, longest visible.......	0.000,077	0.000,030	33,000.	390.000,000,000,000
To long to be visible.........	Infra-red (heat) longest.....	0.03	0.012	85.	990,000,000,000
	Electric (wireless), shortest.	0.2	0.079	13.	150,000,000,000
	Electric (wireless), longest..	1,000,000.	390,000.	0.000,002	30,000

180. Different Wave Lengths Cause Different Color Sensations.—See Table 179. When the vibrations of the particles of a heated substance become so frequent that 400,000,000,000,000 waves are transmitted per second (wave length = about $\frac{1}{34,000}$ in.) the color sensation of red results. If the substance is heated to higher temperatures, its molecules vibrate still more rapidly as its temperature increases. Its colors then successively are: (1) *Red.* (2) *Blood Red.* (3) *Dark Cherry.* (4) *Medium Cherry.* (5) *Cherry or Full Red.* (6) *Bright Red.* (7) *Salmon.* (8) *Orange.* (9) *Lemon.* (10) *Light yellow.* (11) *Straw.* (12) *Light straw.* (13) *White.* Each color corresponds to a certain temperature as shown in Table 63. These colors are utilized as temperature indication in tempering steel.

NOTE.—WHEN A BEAM OF SUN LIGHT IS BROKEN UP INTO ITS DIFFERENT COMPONENT COLORS, BY THE INTERPOSITION OF A GLASS PRISM in its path, the colors in the resulting *spectrum* appear (Table 179), in a descending progression as to wave-length, as *red, orange, yellow, green, blue, indigo,* and *violet.* This shows that the light emitted by the sun is due to waves of all visible lengths. We know, from common observation, that heat waves are also radiated from the sun. It has also been shown by careful experiments that all "light" waves are, at the same time, radiant "heat" waves—that is, that all light waves will heat a substance in which they are absorbed.

181. The Specific Purpose Of All Forms Of Illuminating Devices, Or Lamps, Is To Disseminate Æther Waves.—In the design of lamps it is particularly sought to secure a maximum of lighting effect with a minimum accompaniment of heat. Perfection in the operation of a lamp would be attained if it emitted light waves only without heat waves. Since, however, light waves are at the same time heat waves, the desired result has never been realized. Issuance of light with practically no liberation of heat may be observed in the physiological processes of the glowworm and firefly, and in certain other phosphorescent phenomena. In these, the rate at which the heat is liberated is so slow that the temperature, of the so-called "heatless?" light sources, remain low. But artificial duplication of these natural processes, upon a commercially practicable scale now appears to be unattainable.

NOTE.—AN ORDINARY KEROSENE LAMP, gives off as light (luminous radiant energy) only about 0.04 per cent. of the available energy in the oil. The remaining energy is dissipated in the surrounding air as non-luminous, radiant energy and in heating the air by conduction. Carbon-filament electric lamps give out, as light, only about 0.4 per cent. of the electrical energy which they consume. Gas-filled Mazda lamps give out about 3.0 per cent. Some highly efficient arc-lamps give out as light 7.0 per cent. of the total electrical energy which they consume; the remainder, 93 per cent., is given out as heat which warms the surrounding atmosphere and objects.

NOTE.—THE EFFICIENCY OF A LAMP ORDINARILY INCREASES AS THE TEMPERATURE OF THE ILLUMINATING ELEMENT INCREASES.—The filament-temperature in a gas-filled electric lamp is much higher than in any other type of electric filament lamp. This accounts for its relatively high efficiency.

NOTE.—MOMENTARY REDUCTIONS OF THE VOLTAGE WHICH OPERATES AN ELECTRIC LAMP RESULTS IN CORRESPONDING MOMENTARY DIMINISHMENTS OF ITS LIGHTING EFFECT.—A small voltage-diminishment produces a considerable decrease in lighting effect. Such fluctuations of emitted light are due directly to the very slight decreases in filament-temperature which attend the momentary drop of voltage. On the other hand if the temperature of the filament is kept higher than that for which it was designed, the "life" of the lamp will be greatly curtailed. Hence the importance of maintaining the filaments at as high—but at no higher—a working temperature as is consistent with considerations of durability is evident. This subject is discussed fully in the author's PRACTICAL ELECTRICAL ILLUMINATION and AMERICAN ELECTRICIANS' HANDBOOK.

182. If The Temperature Of An Electrical Conductor Be Increased, Its Resistance To Current Flow Will Generally Be Increased.—Thus the power available at the receiving end of a transmission line may decrease as the temperature of its conductors increases. This principle is utilized in certain temperature-measuring instruments. See Sec. 669 for a description of a resistance pyrometer.

NOTE.—THE ATTRACTIVE FORCE OF A PERMANENT MAGNET is decreased by applications of heat. Thus if a horseshoe magnet is heated its magnetic strength is decreased. This effect of heat can be verified by the following simple experiment: Take an ordinary darning needle and stroke it over a permanent magnet a few times. The darning needle will then attract other needles; that is, it has been magnetized. If the needle is then heated in a flame to a red heat and allowed to cool, it will be found that it does not attract other needles anymore; hence it has lost its magnetism.

183. Table Showing Strengths Of Metals At Various Temperatures.—The strength of the metal at 70° F. is taken as the basis for comparison. These data are plotted into the graphs of Figs. 177 and 178.

Metal		Strengths at different temperatures (Fahrenheit)								
		70°	210°	400°	570°	750°	930°	1,100°	1,300°	1,475°
Bronze	Lb. per sq. in.	50,000	50,500	47,000	28,500	13,000	9,000			
	Per cent.	100	101	94	57	26	18			
Cast iron	Lb. per sq. in.	15,000	......	15,000	14,850	13,800	11,400	6,300		
	Per cent.	100	......	100	99	92	76	42		
Cast steel	Lb. per sq. in.	70,000	76,400	87,600	84,700	67,900	39,900			
	Per cent.	100	109	125	121	97	57			
Copper	Lb. per sq. in.	35,000	33,200	29,800	25,600	20,600	14,700			
	Per cent.	100	95	85	73	59	42			
Structural steel	Lb. per sq. in.	60,000	61,800	79,200	73,200	51,600	29,400	16,800		
	Per cent.	100	103	132	122	86	49	28		
Wrought iron	Lb. per sq. in.	48,000	50,000	53,800	55,800	46,100	36,500	20,200	12,000	7,200
	Per cent.	100	104	112	116	96	76	42	25	15

184. The Strengths Of Metals May And Generally Do Vary With Their Temperatures.

—High temperatures (Table 183—Figs. 177 and 178) generally reduce the strengths of metals.

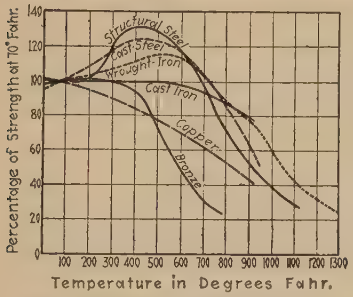


FIG. 177.—Showing percentage variation in strength of different metals with variation in temperature. (Values computed from those of Fig. 178.)

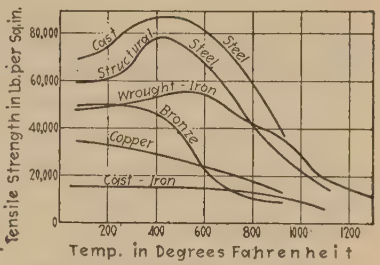


FIG. 178.—Graph showing variation of strengths of metals as temperature rises. (Plotted from values in MACHINERY'S HANDBOOK, p. 300.)

But low temperatures may also produce weakening effects; a freezing temperature (32° F.) renders steel, very brittle. Other metals also become extremely brittle at low temperature.

QUESTIONS ON DIVISION 6

1. What are the three possible effects of adding heat to a substance or abstracting heat from it?

2. What is a *property* of a substance. Name several properties. Can properties be changed?

3. Define a *process.* Give several examples of processes.

4. What is a physical process? Give several examples. In this division, what physical processes are discussed?

5. Explain the difference between a reversible and an irreversible physical process and give examples of each. Into which class do most physical processes fall?

6. What is a chemical process? What four general types of chemical process are there? Explain each and give examples.

7. Explain what heat effects may accompany chemical reactions. Give examples.

8. Define *dissociation.* What is the difference between a dissociation and a decomposition? Give examples to illustrate the difference.

9. What causes a body to expand? Explain.

10. What is *contraction?*

11. How may expansion of materials be utilized for doing work? Describe two examples in full.

12. What is *melting? Fusing?*

13. What is the transition of a substance from liquid to vapor called?

14. Does the temperature of a substance change while the substance is in process of melting? While in process of vaporization?

15. Does melting or vaporization of a substance require absorption of additional heat by the substance?

16. Give some examples of the sublimation of solids.

17. Explain what happens when a solid sublimes.

18. What is *viscosity?*

19. How is a solid distinguished from a liquid?

20. What is the effect of temperature upon the viscosity of a substance?

21. How does a liquid manifest *mobility?*

22. What, in general, is *specific viscosity?*

23. At what temperatures are the specific viscosities of substances defined?

24. How does temperature affect the gas-absorptive property of solids?

25. Explain fully how gases are absorbed in solids.

26. Give examples and uses of gas-absorptive solids.

27. State the phenomena by which the gas-absorptive property of liquids may be demonstrated.

28. What liquid is it that will dissolve a greater number of different solids than any others? Name other solvents.

29. Upon what factors does the dissolving capacity of a liquid depend?

30. What effect does the dissolving of a solid in a liquid have on the temperature of the solution. Discuss in full.

31. Do vapors carry solids in solution? What is the special significance of this fact in power-plant operation?

32. How is scale formed in a steam boiler?

33. Describe an apparatus for generating electrical energy directly from heat. How is it used commercially?

34. What is light? What are some of the characteristics of light? What is the cause of light? What is color? What is the relation of color to temperature.

35. Are ordinary lamps efficient in their production of light? What effect do changes of temperature of the illuminating element of an electric lamp, produce in the quality of the light afforded?

36. How does temperature affect the strength of metals?

37. How is the electrical resistance of a substance dependant on its temperature? What commercial use is made of this fact?

DIVISION 7

EXPANSION AND CONTRACTION OF SOLIDS AND LIQUIDS

185. "Addition Of Heat Causes Expansion, Withdrawal Of Heat Causes Contraction" (Fig. 179) is, in general, true for all substances. There are, however, certain exceptions; see Sec. 187. This subject has already been discussed, briefly, in Sec. 159. There it was explained that addition of heat causes an increase in molecular vibration. Hence, expansion results. Withdrawal of heat causes a decrease in molecular vibration. Thereby, contraction ensues. In this division, the subject will be treated in more detail.

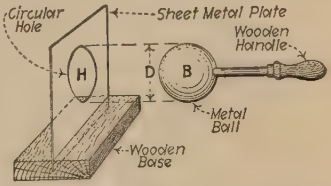


Fig. 179.—Heat expands objects. (When cold, both the hole *H* and ball *B* are of the same diameter, then *B* will just pass through *H*. But, when *B* is heated, it will not pass through *H*.)

186. Expansion And Contraction Of Solids will be considered first. In general, when the temperature of any solid is increased, it becomes larger. When its temperature is decreased, it becomes smaller. Many examples of these phenomena are familiar to all.

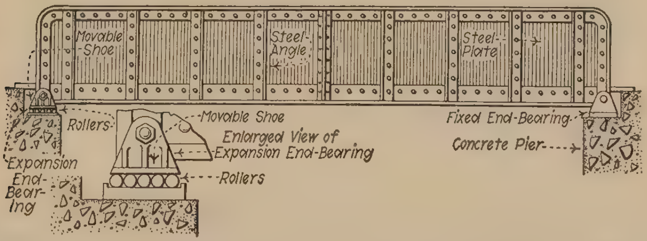


Fig. 180.—Girder bridge with provision for expansion (bridges over 100 ft. long usually have roller bearings; from 50 to 100 ft. span may have friction shoes instead of roller shoe).

EXAMPLES.—Electric wires on pole-lines sag further on a hot day than on a cold day. Railway track-rails expand on hot days, and buckle. This may cause wrecks. Steel bridges have expansion joints (Figs. 180 and 181), so that expansion of the span will not cause damage. Wagon tires are heated to render them sufficiently large to fit over the felloes; in cooling, the tire contracts and renders the whole very rigid. In making machinery, metal collars are, often, expanded by heat and then allowed to shrink firmly onto shafts. Brick power-house chimneys are often made double so that excessive expansion of the inner shell will not affect the outer. A heated journal in a bearing may expand and become siezed.

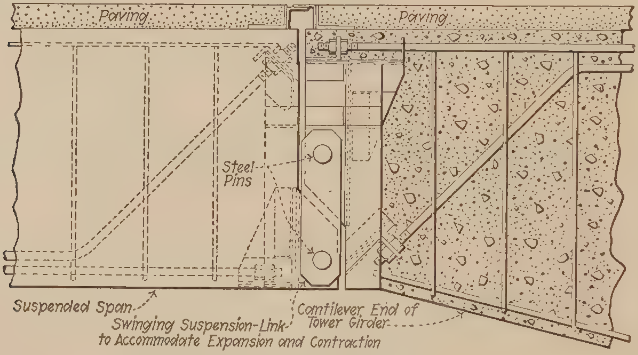

Paving
Paving
Steel Pins
Suspended Span
Swinging Suspension-Link to Accommodate Expansion and Contraction
Cantilever End of Tower Girder

FIG. 181.—Swinging-link expansion joint used in reinforced-concrete viaduct.

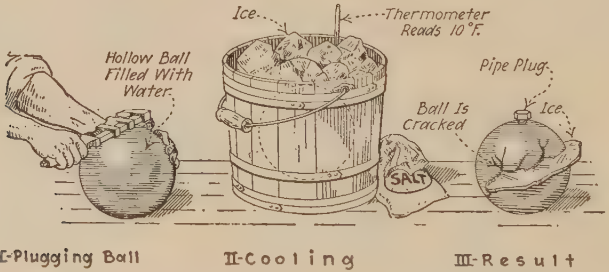


FIG. 182.—Illustrating the effects of freezing in a closed vessel. A hollow cast iron ball filled completely with water and plugged is placed in a pail containing ice and salt. As the water freezes, it *expands* and the force of expansion breaks the ball.

187. Exceptions To The General Rule That Heating Expands Substances And Cooling Contracts Them are these: As water is cooled, it contracts until its temperature has decreased to 39.2° F. (4° C). But as it is cooled further, it expands. It may solidify into ice. But, as is common knowledge, ice occupies greater volume than the water from which it forms and may, in freezing, break pipes (Fig. 182) and split rocks. See following Sec. 209 for a further discussion. The metals iron, antimony, and bismuth contract on melting and expand on solidifying. The contrary might reasonably be expected since, obviously, melting requires the addition of heat. On the other hand, certain other metals—gold, silver, and copper, for example—expand in melting and contract in solidifying. Hence, these latter metals cannot conveniently be cast but must be stamped.

188. The Amount Of Expansion For The Same Temperature Increase, Is Different in Different Substances.—Likewise the amount of contraction, for the same temperature decrease, is different. These facts have been verified, experimentally, many times. This property is utilized practically in a number of different devices, as explained in the examples below:

Example.—Rubber (see Table 192) expands 0.000,042,8 of its length for each degree Fahrenheit temperature increase. Cast brass expands 0.000,010,4 of its length per degree Fahrenheit. Thus, the expansion of the rubber is about four times as great as that of brass. Hard glass, however, expands only 0.000,003, 3 of its length per degree Fahrenheit increase.

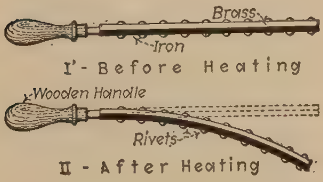


Fig. 183.—The compound bar (cold and heated).

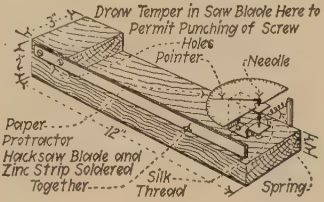

Draw Temper in Saw Blade Here to Permit Punching of Screw Holes
3"
2"
Pointer
Needle
Paper Protractor
12"
Hacksaw Blade and Zinc Strip Soldered Together
Silk Thread
Spring

Fig. 184.—Home-made thermometer operating on the compound-bar principle. (L. Pyle in *Popular Mechanics.*)

Example.—If two similar strips of metal which expand at different rates are fastened together (Figs. 183 and 184) by riveting or welding, the strains which occur when the *compound bar* is heated will cause the bar to bend, somewhat as shown in the illustration. This principle is applied in various devices and instruments. The bending is due to the fact that the length of one of the component strips increases more for the same temperature rise than does the length of the other.

Example.—Thermostatic Metal (Figs. 185, 186 and 187) is made by welding together permanently, through their entire length with the oxyacetylene flame, two strips of metal which have widely different expansion coefficients. It is used for temperature indication, temperature control, or temperature compensation in: oven thermometers, electric heaters, ice machines, refrigerators, thermostats, automobile ignition control, battery-charging control, electric-signal control, and carburetors.

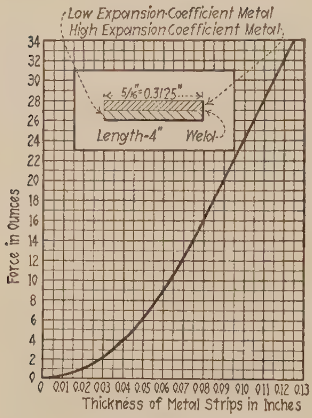


FIG. 185.—Force exerted by a *General Electric Company* thermostatic metal strip for a 100° F. temperature change.

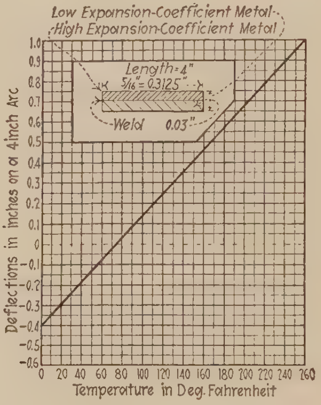


FIG. 186.—Deflection of *General Electric Company* thermostatic-metal strip with the temperature.

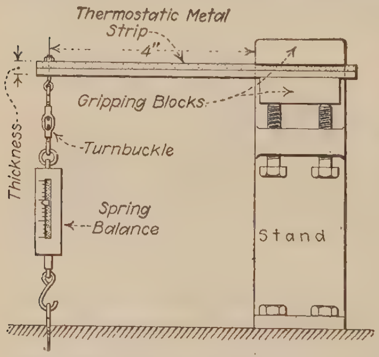


FIG. 187.—Showing probable apparatus employed in testing thermostatic metal strip in determining the values from which Fig. 185 was plotted; the metal strip was probably enclosed in a tube wherein any desired temperature would be provided. The values from which Fig. 186 was plotted were probably obtained by permitting the metal to deflect free—that is, without using the spring balance.

EXAMPLE.—The thermostat (Fig. 188) operates on the compound-bar (Fig. 183) principle. A thermostat may be used for closing the circuit in an electric-signal system, to sound an alarm, if the temperature becomes excessive. Thermostats are also used to regulate the dampers in heating systems. Thereby, they provide automatic heat control. When the room becomes too warm, the thermostat-bar bends in one direction and completes the damper-closing circuit. If the room becomes too cool, the thermostat-bar bends in the other direction, and completes the damper-opening circuit.

Example.—Clock pendulums will, due to temperature changes, vary in length, unless some compensating arrangement is provided.

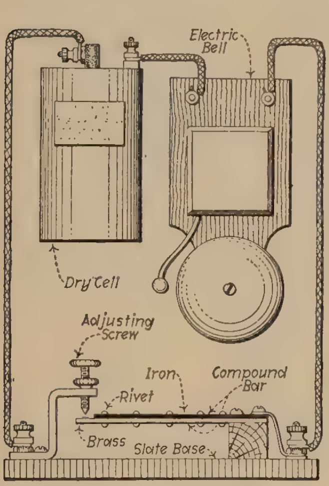


Fig. 188.—The thermostat.

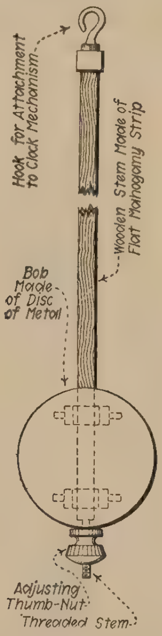

Hook for Attachment to Clock Mechanism
Wooden Stem Made of Flat Mahogany Strip
Bob Made of Disc of Metal
Adjusting Thumb-Nut
Threaded Stem

Fig. 189.—Pendulum with wooden supporting stem to minimize effects of expansion and contraction

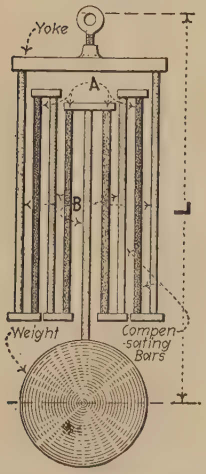


Fig. 190.—Compensated pendulum.

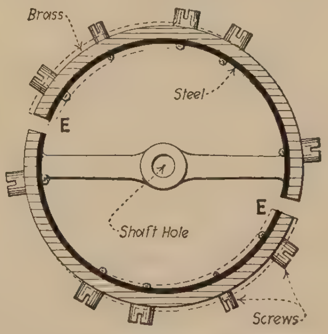


Fig. 191.—Compensated balance wheel for a watch.

Variation in pendulum length may cause the clock to run either too fast or too slow. Wooden stems (Fig. 189) are sometimes used because (see Table 192) wood expands and contracts but slightly with changes in temperature. In the compensated pendulum (Fig. 190) there is, practically, no change in the effective length, *L*. When the metal bars *B* expand, they tend to lengthen the pendulum. But bars *A*, which are of a different metal, expand more than do bars *B*; this tends to shorten the pendulum. The lengths and the materials of *A* and *B*, are so selected that the actual pendulum length, *L*, is always, under reasonable temperature conditions, the same.

Example.—The compensated balance wheel (Fig. 191) of a watch is so made that the ends *E* of the segments adjust themselves according to the temperature of the wheel. Thereby, the watch is caused to run at a constant speed. If the balance wheel were not "compensated," the temperature would affect the speed of the watch. When warm, the oil would be thinner. Also, the diameter of the wheel and the length of the hair spring would be greater. When cool, these effects would be reversed. With a properly compensated wheel, they are, practically, of no consequence.

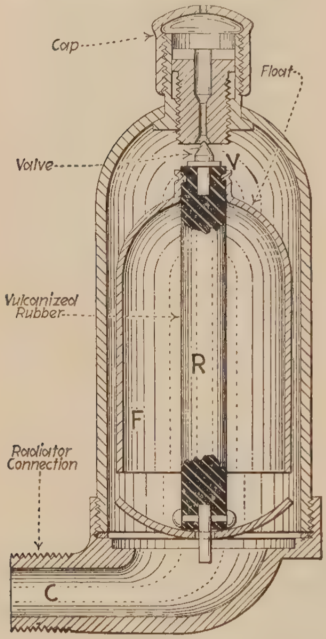


Fig. 192.—"Davis" steam-radiator air valve. (When *R* is surrounded by steam it expands and closes valve, *V*. Or, when water enters the chamber, float, *F*, rises and closes *V*.)

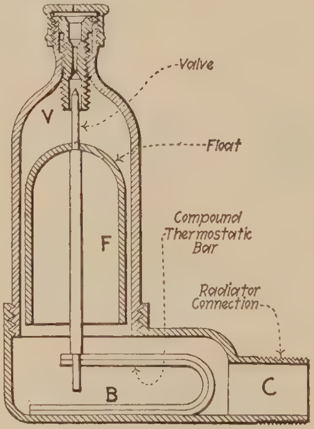


Fig. 193.—The "Onderdonk" radiator air valve. (Float *F*, closes valve, *V*, if water enters it. Bar, *B*, closes *V* after steam has entered it. The valve remains open when there is only cold air in it.)

Example.—Air Valves In Steam-heating Radiators (Figs. 192 and 193) may be automatically controlled by utilizing the compound-bar principle (Fig. 193) or by the expansion (Fig. 192) of a rubber post.

189. Expansion May Be Considered Under Three Different Headings: (1) *Lineal expansion, which is increase in length.*

(2) *Surface, superficial, or areal expansion, which is the increase in area of a surface when it is heated.* (3) *Volumetric expansion, which is increase in volume.* Obviously, there may likewise be lineal contraction, superficial contraction and volumetric contraction. Each of these phenomena will be considered.

190. The Coefficient Of Lineal Expansion is defined as the ratio of the increase in the length of a bar of material to its original length when the temperature of the material is increased 1° F. (or C.). A more practical definition is (Fig. 194) this: *The coefficient of lineal expansion is the increase in length, in inches, due to a temperature increase of 1° F. (or C.) in a bar of the material which was originally 1 in. long.* It is the increase in length, in inches per inch of original length, per degree temperature difference.

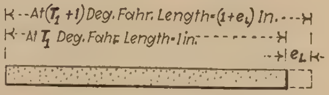

At (T_1+1) Deg. Fahr. Length = $(1+e_L)$ In.
At T_1 Deg. Fahr. Length = 1 in.
e_L

FIG. 194.—Illustrating coefficient of lineal expansion.

NOTE.—A COEFFICIENT OF EXPANSION CAN BE OBTAINED BY CONSIDERING THE DECREASE IN LENGTH, due to a temperature decrease, as well as by considering the increase in length, due to a temperature increase. Hence, the same coefficient is used in computing either contraction or expansion. Table 192 specifies some coefficients of lineal expansion.

191. A Coefficient Of Expansion Computed On The Basis Of The Above Definition Is Not Absolutely Accurate.—The exact value of an expansion coefficient depends upon the temperature at which the coefficient is determined. Likewise, the coefficient values given in Table 192 are not strictly accurate for every temperature. But the expansion coefficient values of any material differ, at different temperatures, from the values of the table so little that the errors which they may introduce through their application are of absolutely no consequence in any practical problem. A similar situation obtains for coefficients of areal or surface expansion (Sec. 199) and cubical-expansion coefficients (Sec. 202). For pure metals, the coefficient generally increases with the temperature. For alloys, there appears to be no general rule.

EXAMPLE.—As taken from the SMITHSONIAN PHYSICAL TABLES, the coefficient of lineal expansion of aluminum at 100° F. = 0000.,012,8; at 1,112° F. = 0.000,017,5.

192. Table Showing Coefficients Of Lineal Expansion Of Some Common Materials.—The tabulated values are equivalent to the expansion (or contraction), in inches, in each 1 in. original length, for each 1° F. increase (or decrease) in temperature. The values given here are the average values of the coefficient of lineal expansion between the temperatures 32 and 212° F.

Material, metals	Average coefficient of lineal expansion	Material, various	Average coefficient of lineal expansion
Aluminum	0.000,012,3	Brick	0.000,003,1
Aluminum bronze	0.000,009,4	Carbon, coke	0.000,003,0
Antimony	0.000,005,8	Cement, neat	0.000,006,0
Brass, cast	0.000,010,4	Concrete	0.000,008,0
Brass, wire	0.000,010,7	Glass, thermometer	0.000,004,5
Bronze	0.000,010,0	Glass, hard	0.000,003,3
Copper	0.000,009,3	Glass, plate and	
German silver	0.000,010,2	crown	0.000,005,0
Gold	0.000,008,2	Granite	0.000,004,8
Iron, pure	0.000,006,7	Graphite	0.000,004,4
Iron, cast	0.000,005,9	Limestone	0.000,001,4
Iron, soft forged	0.000,006,3	Marble	0.000,006,5
Iron, wire	0.000,008,0	Masonry, from	0.000,002,5
Lead	0.000,015,1	to	0.000,005,0
Magnesium	0.000,014,5	Porcelain	0.000,001,7
Phosphor bronze	0.000,009,4	Rubber	0.000,042,8
Silver	0.000,010,7	Vulcanite	0.000,040,0
Solder	0.000,013,4	Wood, oak:	
Steel, Bessemer:		parallel to fiber	0.000,002,7
rolled hard	0.000,005,6	across fiber	0.000,003,0
rolled soft	0.000,006,3	Chestnut:	
Steel, nickel (10%		parallel to fiber	0.000,003,6
Ni)	0.000,007,3	across fiber	0.000,001,9
Tin	0.000,012,7	Ash:	
Type metal	0.000,010,8	parallel to fiber	0.000,005,3
Zinc	0.000,016,5	Pine:	
Zinc (cast)	0.000,010,6	parallel to fiber	0.000,003,0

193. Apparatus For The Determination Of The Coefficient Of Expansion utilizes the general principles indicated in Figs. 195 and 196. For tests where precise values are unnecessary, an equipment, similar to that of Fig. 195 may be used for determining the lineal expansion of metals. For a very accurate determination, microscopes (Fig. 196) may be employed for measuring the increase in length.

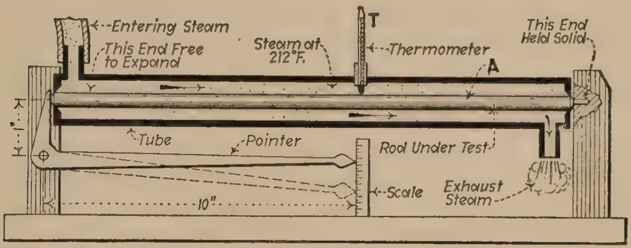


FIG. 195.—An apparatus for determining the coefficient of lineal expansion.

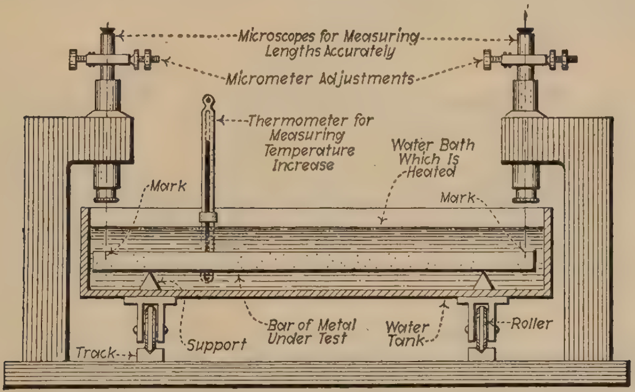

Microscopes for Measuring Lengths Accurately
Micrometer Adjustments
Thermometer for Measuring Temperature Increase
Water Bath Which Is Heated
Mark
Mark
Bar of Metal Under Test
Water Tank
Roller
Support
Track

FIG. 196.—Equipment for precise coefficient-of-lineal-expansion determinations.

194. The Formula For Computing The Coefficient Of Lineal Expansion, which follows from the definition given in preceding Sec. 190 is:

$$e_L = \frac{L_2 - L_1}{L_1(T_2 - T_1)} \qquad \text{(coef. of linear expan.)} \tag{91}$$

or, since $l = {}_2 - L_1$:

$$e_L = \frac{l}{L_1(T_2 - T_1)} \qquad \text{(coef. of linear expan.)} \tag{92}$$

Wherein: e_L = the coefficient of lineal expansion. L_1 = the length of the material, measured in any unit, at the temperature T_1. L_2 = the length of the material, measured in the same unit as L_1, at temperature T_2. T_1 and T_2 = respectively, the temperatures in degrees Fahrenheit. l = increase in length due to expansion, in the same unit as L_1.

Note.—If The Original Length, L_1, Of The Material Is Unity, say 1 ft., and the temperature change is 1° F., then For. (91) becomes:

(93) $$e_L = L_2 - 1$$ (coef. of linear expan.)

Example.—At a room-temperature of 72° F., the length of the copper rod *A*, in Fig. 195, is 24 in. When the thermometer, *T*, reads 212° F., the rod length has increased 0.031,2 in. What is the coefficient of lineal expansion of copper? Solution.—Substituting in For. (92): $e_L = l/L_1(T_2 - T_1) = 0.031{,}2 \div [24 \times (212 - 72)] = 0.031{,}2 \div (24 \times 140) = 0.031{,}2 \div 3{,}360 = 0.000{,}009{,}3$ = *coefficient of lineal expansion of copper*, as shown in Table 192.

195. The Formula For Computing The Amount Of Lineal Expansion Or Contraction When An Object Is Heated Or Cooled is this:

(94) $$l = e_L L_1 T$$ (inches)

Wherein: l = increase in length due to expansion, or decrease in length due to contraction, in inches. L_1 = the length of the object before heating or cooling, in inches. e_L = coefficient of lineal expansion from Table 192. T = the temperature increase or decrease, in degrees Fahrenheit. (L_1 may be expressed in feet or any unit of lineal measure; then l will be in the same unit.)

Derivation.—By definition (Sec. 190) the coefficient of expansion e_L, is merely the expansion increase (or the contraction decrease) in inches, per inch original length, per degree temperature difference. Hence, to obtain the amount of expansion or contraction, it is merely necessary to multiply together the original length, the expansion coefficient and the temperature difference. These are the operations which For. (94) indicates.

Example.—An iron rod which is 10 ft. long has its temperature raised 25° F. What is its increase in length? Solution.—For iron, from Table 192, $e_L = 0.000{,}006{,}3$. Now, 10 *ft.* = 10 × 12 *in.* = 120 *in.* Substituting in For. (94), the increase in length is: $l = e_L L_1 T = 0.000{,}006{,}3 \times 120 \times 25 = 0.018{,}9$ *in.*

Example.—A steel bridge is 872 ft. long. The variation of temperature in the locality, from the lowest winter to the highest summer temperature, is 135° F. What is the maximum change in the length of the bridge? SOLUTION.—From Table 192, e_L for steel = 0.000,006,3. Now, 872 *ft.* = 872 × 12 *in.* = 10,464 *in.* The increase in length is: $l = e_L L_1 T = 0.000{,}006{,}3 \times 10{,}464 \times 135 = 8.9$ *in.*

EXAMPLE.—What will be the change in length of a copper wire, strung between two poles which are set 120 ft. apart, when the temperature change is 120° F.? Neglect the elasticity and sag of the wire. SOLUTION.—From Table 192, e_L for copper wire = 0.000,009,3. Also, 120 *ft.* = 120 × 12 *in.* = 1,440 *in.* By For. (94); $l = e_L L_1 T = 0.000{,}009{,}3 \times 1{,}440 \times 120 = 1.6$ *in.*

196. The Formula For Computing The Final Length Of A Material After It Has Been Heated (Fig. 197) is given below. This is the same as For. (94) except that the original length, L_1, is added in the right-hand member.

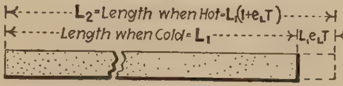


FIG. 197.—Lineal expansion of bar of any length.

(95) $$L_2 = L_1 + L_1 e_L T \qquad \text{(inches)}$$

or:

(96) $$L_2 = L_1(1 + e_L T) \qquad \text{(inches)}$$

or, substituting in (96) for T its equivalent $(T_2 - T_1)$:

(97) $$L_2 = L_1 + L_1 e_L (T_2 - T_1) \qquad \text{(inches)}$$

EXAMPLE.—What will be the length of a cast-brass rod, at 200° F., if the length at 40° F., is 20 in.? SOLUTION —The lineal-expansion coefficient of cast-brass is, from Table 192, 0.000, 010,4. Now, substituting in For. (97): $L_2 = L_1 + L_1 e_L (T_2 - T_1) = 20 + [20 \times 0.000{,}010{,}4 \times (200 - 40)] = 20 + [0.000{,}208 \times 160] = 20 + 0.033 = 20.033$ *in.* = *length at* 200° F.

197. For Computing The Final Length Of A Material After It Has Been Cooled, For. (97) becomes:

(98) $$L_2 = L_1 - L_1 e_L (T_2 - T_1) \qquad \text{(inches)}$$

198. Areal, Surface, Or Superficial Expansion (Fig. 198) is the increase in the area of a surface when it is heated. It is evident that the surface of any material will be larger, after heating than before, since the lineal expansion occurs in each of its two principal directions.

199. The Coefficient Of Areal Expansion is taken as *twice the coefficient of lineal expansion.* Strictly, this is not true.

But the error which the assumption introduces is of no consequence, practically.

Explanation.—Consider a copper plate (Fig. 198) which is 1 in. square. Its area is: 1 × 1 = 1 *sq. in.* Now if this sheet is heated, it will expand lineally in two directions: Both its length and width become greater by an amount e_L. Obviously, the sheet is now $(1 + e_L)$ in. square. Hence, its area is now $(1 + e_L) \times (1 + e_L) = (1 + e_L)^2 = 1 + 2e_L + e_L^2$. Substituting in this formula and taking the lineal expansion coefficient for copper as 0.000,009 from Table 192, the following results: $1 + 2e_L + e_L^2 = 1 + (2 \times 0.000,009) \div (0.000,009)^2 = 1 + 0.000,018 + 0.000,000,000,081 = 1.000,018,000,081 =$ *areal expansion coefficient for copper.* It is evident that the value equivalent to e_L^2, which is 0.000,000,000,081, is so small that its omission from the coefficient would result in no material error. It is, therefore, apparent that for all practical purposes it is sufficient to assume that coefficients of areal expansion may be taken as twice those of lineal expansion, which are given in Table 192.

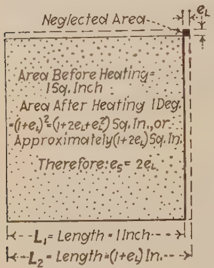

Neglected Area
e_L
Area Before Heating = 1 Sq. Inch
Area After Heating 1 Deg. = $(1+e_L)^2 = (1+2e_L+e_L^2)$ Sq. In., or Approximately $(1+2e_L)$ Sq. In.
Therefore: $e_S = 2e_L$
L_1 = Length = 1 Inch
L_2 = Length = $(1+e_L)$ In.

Fig. 198.—Illustrating derivation of coefficient of areal expansion.

200. The Formula For Computing Increase In Area, Due To Areal Expansion, which follows from the statements of Secs. 198 and 199, is this:

$$A = e_S A_1 T \qquad \text{(square inches)} \tag{99}$$

Wherein: A = increase in area, due to expansion, or decrease in area, due to contraction, in square inches. e_S = coefficient of areal expansion = 2 × *lineal-coefficient value* from Table 192. T = the temperature increase or decrease in degrees Fahrenheit. A_1 = initial area in square inches. A_1 For. (99) may be expressed in square feet or in any unit of areal measure. Then A will be in the same unit.

Example.—A section of street paving which measures 20 × 24 ft. is subjected to a temperature difference of 135° F. If the lineal-expansion coefficient of the material is 0.000,003, what will be the change in area? Solution.—The areal-expansion coefficient will be 2 × 0.000,003 = 0.000,006. Therefore, the change in area will be, For. (99): $A = e_S A_1 T = 20 \times 24 \times 0.000,006 \times 125 = 0.36$ *sq. ft.*

201. Cubical, Cubic, Or Volumetric Expansion (Fig. 199) is the increase which occurs in the volume of a substance when the substance is heated. Cubical contraction is the decrease in volume when the substance is cooled. It is evident from Fig. 199 that when a substance is heated, it expands lineally in all three directions. The change in volume which results is just as definite as a change of length due to lineal expansion.

202. The Coefficient Of Cubical Expansion (Table 207) is assumed to be equal to three times the coefficient of lineal expansion, certain values for which are given in Table 192. While this assumption (see explanation below) is not absolutely accurate, it is sufficiently so for ordinary use.

EXPLANATION.—Assume that the 1-in. cube of Fig. 199 has, before heating, a volume of $1^3 = 1$ *cu. in.* After the temperature of the cube has been increased 1° F., the cube expands the distance e_L in each of the three lineal directions. Hence, the length of each of its sides becomes $(1 + e_L)$. Now the volume of the heated cube will be $(1 + e_L)^3 = (1 + 3e_L + 3e_L^2 + e_L^3)$ cu. in. Now, as demonstrated in explanation under Sec. 199, the values equivalent to $3e_L^2$ and e_L^3 will be so small as to be inconsequential. Hence, they may be disregarded. Therefore, the volume of a heated cube can, with very small error, be taken as $(1 + 3e_L)$ cu. in. In other words, $3e_L$ is the *coefficient of cubical expansion.*

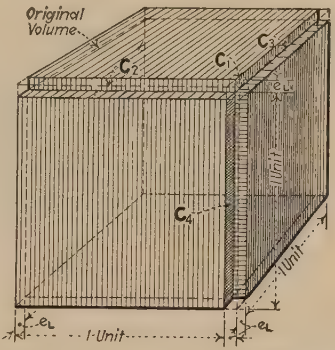


FIG. 199.—Illustrating the cubical coefficient of expansion (the volume of the corners C_1 C_2 C_3 and C_4 are so small as compared with the volume of the whole that they are disregarded in computing the cubical coefficient of expansion).

203. The Formula For Computing The Change In Volume, Due To Cubical Expansion which follows from the preceding discussion and statements is:

$$V = 3e_L V_1 T \qquad \text{(cubic inches)} \tag{100}$$

Wherein: V = change in volume, due to expansion or contraction, in cubic inches. V_1 = the original volume of the substance, in cubic inches. Other symbols have the meanings hereinbefore specified. V_1 (For. 100) may be expressed in cubic feet or in any other unit of cubical measure. Then, V will be in the same unit.

EXAMPLE.—A block of concrete is 30 ft. wide, 17 ft. high, and 4 ft. thick. What will be the change in its volume, when its temperature is changed 50° F.? SOLUTION.—From Table 192, the *lineal-expansion coefficient for concrete* = 0.000,008. Then the *cubical-expansion coefficient* = 3 × 0.000,008 = 0.000,024. The *original volume* = 30 × 17 × 4 = 2,040 *cu. ft.* Now, substituting in For. (100): $V = 3e_LV_1T = 0.000{,}024 \times 2{,}040 \times 50 = 2.45$ *cu. ft.*

204. The Formula For Computing The Volume Of Any Substance, After It Has Been Heated Or Cooled, Is:

$$V_2 = V_1(1 + e_VT) \qquad \text{(cubic inches)} \tag{101}$$

Wherein: V_2 = final volume, in cubic inches. V_1 = original volume, in cubic inches. e_V = coefficient of cubical expansion from Table 207, or $e_V = 3e_L$, as taken from Table 192. T = the temperature increase or decrease, in degrees Fahrenheit.

205. The Expansion Of Liquids has been mentioned in the preceding discussion (Sec. 57) of thermometers. All liquids, with the exception of water, as explained below, expand when heated and contract when cooled. This property renders possible the mercury thermometer. Due to their expansion, all liquids increase in volume when heated (except some when near the freezing point). In general for any given solid the change in volume per degree temperature difference is practically the same, regardless of the original temperature under consideration. But for liquids this is not true. With different liquids the change in volume, per degree temperature difference, varies somewhat according to the temperature under consideration; the coefficient is greater at high than at low temperature. However, for practical engineering purposes, average values (Table 207) may be taken.

NOTE.—THE EXPANSION OF LIQUIDS IS CUBICAL.—Hence, the preceding formulas which were given for computing cubical expansion are the ones which are applied for figuring the expansion of liquids.

206. Coefficients Of Cubical Expansion of Liquids Are Difficult Of Accurate Determination.—The liquid under observation must be contained in a vessel, the material of which has an expansion coefficient different from that of the liquid. However, compensation for the possible error, thus introduced, may be made.

EXAMPLE.—Compensated clock pendulums may be made (Fig. 200 and 201) with mercury, in glass vessels, constituting a "bob." When the rod, *R*, expands downwardly, the mercury, *M*, expands upwardly.

Thereby, assuming correct design, the effective length of the pendulum remains unchanged.

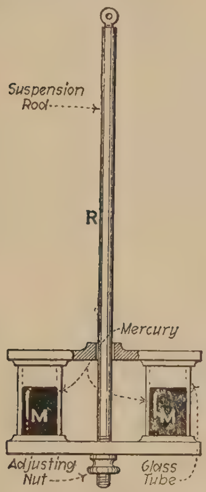


Fig. 200.—The mercury-compensated pendulum.

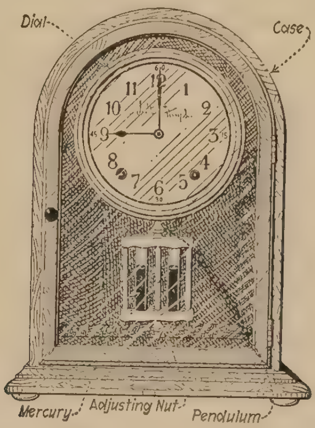


Fig. 201.—Clock equipped with mercury-compensated pendulum.

207. Table Showing Coefficients Of Cubical Expansion Of Some Common Liquids And Solids.

Material	Coefficient of cubical expansion	Material	Coefficient of cubical expansion
Acetic acid	0.000,80	Olive oil	0.000,41
Alcohol (ethyl)	0.000,61	Petroleum	0.000,55
Alcohol (methyl)	0.000,80	Sodium chloride:	
Benzine	0.000,77	1.6 per cent. solution	0.000,60
Benzol	0.000,70	26 per cent. solution	0.000,24
Calcium chloride 5 to 50 per cent. solution	0.000,28	Sulphuric acid	0.000,27
Chloroform	0.000,77	Sulphuric acid, 50 per cent. solution	0.000,45
Ether	0.001,21	Turpentine	0.000,56
Glycerine	0.000,28	Water	0.000,10
Hydrochloric acid	0.000,27	Ice (4 to 30° F.)	0.000,62
Hydrochloric acid 50 per cent. solution	0.000,50	Paraffin wax	0.000,61
Mercury	0.000,10	Rocksalt	0.000,67
		Sulphur	0.000,40

Example.—An open tank contains 6,700 gallons of water of 60° F. How many gallons will it contain, if the temperature of the water is increased to 105° F.? Solution.—From Table 207, the cubical coefficient of expansion of water is 0.000,1. The *change in temperature* = $T = 105 - 60 = 45°$ F. Now, substituting in For. (101): $V_2 = V_1(1 + evT) = 6{,}700 \times [1 + (0.000{,}1 \times 45)] = 6{,}730.15$ *gal.*

208. Liquids Are Practically Incompressible.—The amount which they may be compressed is exceedingly small. Hence, when the liquids which completely fill closed vessels are heated, the resulting pressure, due to their expansion, may be enormous. Serious distortions and ruptures in containing vessels may result through disregard of this fact.

Example.—In hot-water heating systems an *expansion tank* is located near the top of the building; see Div. 17. Into this tank, the water expands, when heated. If the expansion tanks or other suitable arrangements were not provided, the enormous pressure which would be developed in the system by heating of the water might cause valve leakage, and the breaking of radiators, valves, or fittings.

209. The Peculiar Expansion And Contraction Of Water (Fig. 202) will now be considered. Since water is the most common liquid it will be discussed herein at some length. All liquids with certain exceptions, water for example, (Figs. 203 and 204) contract when cooled. When water is cooled its volume changes considerably, as is shown by the graph (Fig. 202). But at about 39° F. it is (Fig. 205) at maximum density. That is, it weighs more, per unit of volume, at this tem-

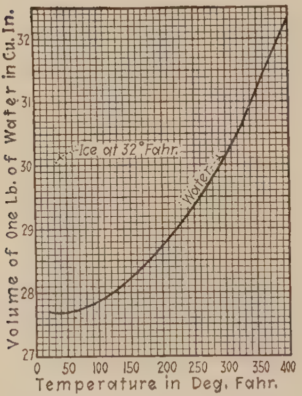


Fig. 202.—Graph showing change in volume of water as it is heated.

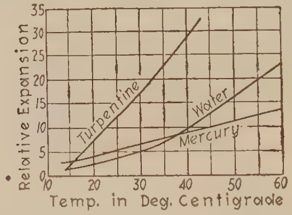


Fig. 203.—Expansion of turpentine as compared to water and mercury (although the graphs for mercury and turpentine appear to be straight lines, they actually curve somewhat. The curvature is too small to be detectable with the scales shown.)

perature than at any other temperature. If it is cooled below this temperature, it begins to expand. This is a peculiar characteristic of water. After cooling to 32° F. it solidifies into ice and the freezing is accompanied by farther expansion.

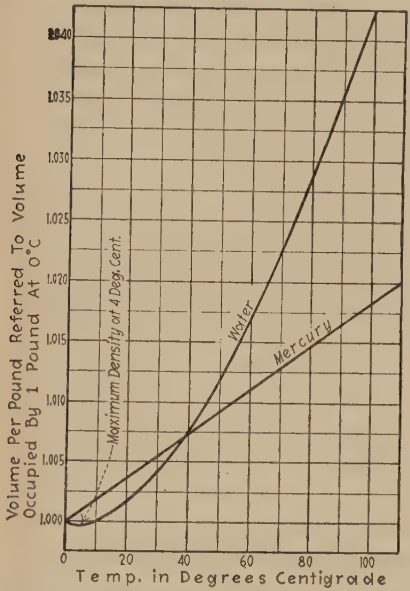


FIG. 204.—Graph comparing the change in densities of mercury and water at different temperatures.

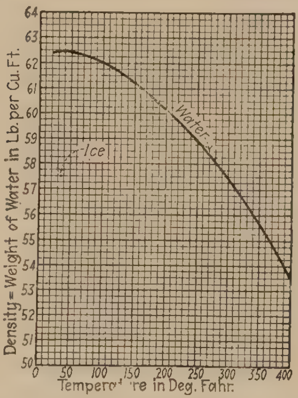


FIG. 205.—Change in weight of water as temperature is changed.

NOTE.—EXPANSION, AT FREEZING TEMPERATURE, IS A VERY IMPORTANT ATTRIBUTE OF WATER.—It is Nature's provision against the oceans, lakes and rivers freezing to the bottom. Ice forms at the surface of the water and being lighter than water remains there. Thus it covers or blankets the water beneath. It prevents the lower strata of water from becoming cooled to the freezing stage.

210. When Water At A Temperature Above 39° F. Is Heated, It Expands.—Its density then diminishes and it becomes "lighter." That is, its weight per unit of volume decreases. This property is very important in certain heating processes.

EXAMPLE.—When heat is applied to the bottom of a tank which contains water, a circulation of the water immediately ensues. The stratum of water in contact with the bottom is heated. Thus it is caused to expand. It becomes less dense, or "lighter" than the water above. The cooler, and heavier, water at the top then circulates to the bottom. It thereby displaces the heated water, which ascends to the surface.

Hot water may thus be drawn from the top of a tank before the entire mass of water is heated.

211. The Expansive Property Of Water Is Utilized In Hot-water Heating Systems.—The cooler, and heavier, water flows into the boiler, or heating element, at the bottom. Therein it becomes (Fig 126) heated and expanded. It then flows through the radiators and gives up some of its heat to the air in the rooms. When it leaves the radiators, it is again comparatively cool. It then flows down to the boiler through the return pipe. A continuous circulation is thus maintained.

212. Differences Of Expansion And, Therefore, Of Density Between Different Parts Of A Volume Of Water Cause Currents To Circulate Therein.—These are called *convection currents*. The rapidity with which water may be heated depends upon the rapidity of these currents. Without them it would be difficult to heat water in any form of vessel, whether a teakettle on a kitchen stove or a steam boiler in a power plant. Water is a very poor conductor of heat. Hence, this property (conduction) is not effective in carrying heat quickly to all parts of a mass of water.

213. Freezing Water Exerts An Enormous Expansion Force (Figs. 182 and 206). Ordinarily, one cubic foot of water becomes about 1.085 cu. ft. of ice. The expansion is about 8.5 per cent. The expansion of a body of water, by freezing into ice, thus amounts to more than one-twelfth of the initial volume of the water. If water is frozen in a closed vessel, the expansion of the ice thus formed may, and generally will, rupture the vessel, even though the vessel be made of iron or steel.

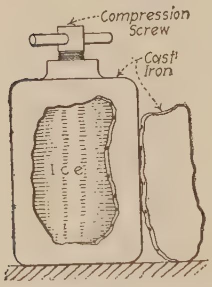


Fig. 206.—The result of water frozen in a closed cast-iron vessel. (Actually the expanding ice, which breaks a vessel, issues from the hole which it makes as shown in Fig. 182.)

Example.—A gallon of water contains 231 cu. in. Hence, if a gallon of water freezes to ice at 32° F., the volume of the ice will be 231 × 1.085 = 249.64 cu. in.

Note.—The Molecules Of Water In The Form Of Ice Are Closer Together Than Are The Molecules Of Liquid Water.— Thus the behavior of water, when passing from the liquid to the solid state, presents no exception to the general law (Sec. 50) which governs molecular action in substances from which heat is extracted. The apparent anomaly observed in the expansion of ice is explained on the hypothesis that the molecules of ice group themselves into crystals. Thus, while the molecules are more compactly arranged in the ice crystals than in the liquid water, the crystals themselves are separated by comparatively large spaces. Hence, the net effect of the crystalline grouping of the molecules is an increase instead of a diminishment of volume.

214. The Behavior Of Metals When Changing From The Liquid To The Solid State will now be considered. Besides water, cast iron, antimony, and bismuth are, perhaps, the most common substances which increase in volume when freezing or solidifying. When molten cast iron freezes or solidifies in a foundry mold, it expands. However, cast iron contracts about 1 per cent. while cooling from its freezing point to ordinary temperature. Hence, it is often said that cast iron shrinks. Unless proper precautions are taken, this shrinkage may break a casting (Fig. 207). With other metals (Sec. 187) a contrary effect will be noted; that is, they decrease in volume when solidifying. A few common examples of this latter class are mercury, gold, and silver.

Note.—The Expansive Solidification Of Antimony And Its Low Expansion Coefficient Render It Useful As A Type-metal Ingredient.—The sharp outlines requisite in printing type could not be obtained if the cast metal were to contract while solidifying. Ordinary type metal is an alloy of lead, antimony, and copper. The tendency of the antimony to expand neutralizes the tendency of the other ingredients to contract. Thus the volume of the molded metal continues constant during transition from the molten to the solid state.

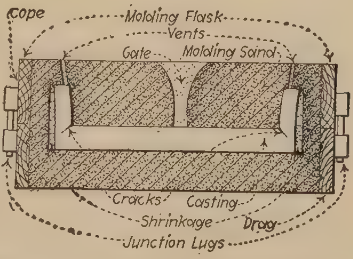


Fig. 207.—Shrinkage causes casting to crack in mold.

Note.—Expansion Of Antimony While Cooling From The Liquid To The Solid State is due to a crystalline arrangement of the molecules similar to that which occurs (note subjoined to Sec. 213) in the freezing of water.

Note.—The Graduation Marks On A Patternmakers' Rule Are Spaced Farther Apart Than Are Those On An Ordinary Standard

Rule.—The increased spacing, on rules used in the making of patterns for iron castings, amounts to ⅛ in. per ft. This is to insure that the patterns will be made enough larger, than the required castings, to compensate for shrinkage of the solid iron in cooling.

Note.—The Excessive Contraction Of Gold And Silver While Cooling From The Liquid To The Solid State Prevents Accurate Casting With These Metals.—The shrinkage of the metal in the mold will invariably result in producing warped castings, with rounded and blunted edges and corners. Hence, as stated in Sec. 187, in the minting of gold and silver currency, the coins are stamped out of the solid metal with steel dies.

215. Table Showing Approximate Lineal Shrinkage Of Castings And Forgings (From Marks' Handbook, page 294).

Metal	Shrinkage ratio	Multiplier	Metal	Shrinkage ratio	Multiplier
Bar iron, rolled.	1:55	1.018,2	Iron, fine grained.	1:72	1.013,9
Bell metal.....	1:65	1.015,4	Lead............	1:92	1.010,9
Bismuth......	1:265	1.003,8	Steel, cast.......	1:50	1.020,0
Brass.........	1:65	1.015,4	Steel, puddled...	1:72	1.013,9
Bronze........	1:63	1.015,9	Steel, wrought...	1:64	1.015,6
Cast iron......	1:96	1.010,4	Tin.............	1:128	1.007,8
Gun metal....	1:134	1.007,5	Zinc, cast.......	1:62	1.016,1

Example.—The shrinkage of a bell-metal casting, while the metal is cooling in the mold, amounts to 1 ÷ 65 = 0.015,4 *in. per inch of length of the final casting.* Hence, the pattern for a bell-metal casting should be 1.015,4 times as long as the required casting.

Example.—An iron casting is required to be 3 ft. long, 8 in. wide, and 2 in. thick. What should be the dimensions of the mold? What will be the percentage of shrinkage in the casting? Solution.—The *volume of the casting* = (3 × 12) × 8 × 2 = 576 *cu. in.* By Table 215 each dimension must be multiplied by 1.010,4. Hence, the length of the mold = 3 × 1.010,4 = 3.031,2 *ft.*, the width = 8 × 1.010,4 = 8.083,2 *in.*, and the depth = 2 × 1.0104 = 2.0208 *in.* Then, *the volume of the mold* = (3.0312 × 12) × 8.0832 × 2.0208 = 594.16 *cu. in.* Hence, *the percentage of shrinkage* = [(594.16 − 576)/594.16] × 100 = 3.06 *per cent.*

216. There Are Two Conditions Under Which A Solid May Expand Or Contract: (1) *The expansion or contraction may be entirely unopposed by counteracting forces.* (2) *The expan-*

sion or contraction, or the tendency thereto, may be opposed or restrained in some manner by counteracting forces. Each of these conditions will be discussed in the following sections. Only unrestrained expansion and contraction have hitherto been considered.

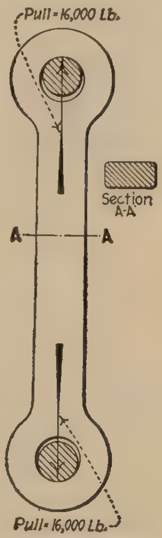


Fig. 208.—Stress due to tension.

217. A Study Of The Phenomena Of Restrained Expansion And Contraction Involves Consideration Of Stresses And Strains In Materials.—When any substance, as a metal wire, is subjected to a pulling force, the force tends to strain the substance by stretching or elongating it. Coincidentally, a stress, which tends to oppose deformation by the pulling force, develops within the substance. When any substance, as a mass of rubber, is subjected to a pressing force, the force tends to strain the substance by crowding its particles closer together. In this case also, a stress, which resists the applied force, develops within the substance. So likewise, when any substance, as a boiler rivet, is subjected to the straining action of a shearing force, a stress develops within the substance. When a substance is subjected (Fig. 208) to a pull or *tension*, the stress developed in the substance thereby is called a *tensile stress*. When a substance is subjected (Fig. 209) to pressure or *compression*, the stress developed in the substance thereby is called a *compressive stress*. When a substance is subjected (Figs. 210 and 211) to a shearing force, the stress developed thereby is called a *shearing stress*. Tensile, com-

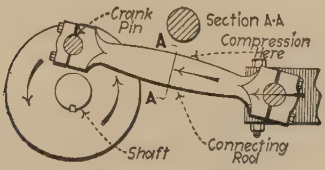


Fig. 209.—Stress due to compression.

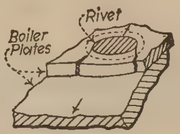


Fig. 210.—Showing a piece being sheared from boiler plate by rivet.

pressive, and shearing stresses are usually expressed in terms of the forces which are applied to produce them, divided by the number of area units in the cross-section of the substance where it opposes the force.

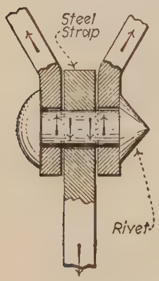


Fig. 211.—Stress due to shear.

Examples.—If a wire of 0.1-sq. in. cross-section suspends a load of 1,600 lb., the *tensile stress* in the wire is 1,600 ÷ 0.1 = 16,000 *lb. per sq. in.* If a steel bridge-rod, of 3-sq. in. cross-section, is subjected to a pull of 150,000 lb., the *tensile stress* in the rod is 150,000 ÷ 3 = 50,000 *lb. per sq. in.* If an iron column of 4-sq. in. cross-section supports a load of 4,000 lb., the *compressive stress* in the column is 4,000 ÷ 4 = 1,000 *lb. per sq. in.*

Note.—"Stress" And "Strain" Are Not Synonymous Terms. A *stress*, as explained above, is the internal opposing force which develops within a substance when an external force, tending to deform the substance, is applied. A *strain* is the deformation, or charge of shape, of a substance within which a compressive or tensile stress has been developed by application of an external force. As noted above, a stress is measured by the intensity of the applied force and by the cross-sectional area of the substance which sustains the force. The corresponding (total) strain is expressed in terms of the change of dimension of the substance, in the line of direction of the applied force. Furthermore, since, under tensile or compressive stress, each inch (or foot) of length of the substance is changed by the same amount, the strain can be expressed as a decimal—it is then called the *unit strain* or simply the *strain*—that is, the number of inches (or feet) that each inch (or foot) has been lengthened or shortened.

Example.—If a metal wire, of 10-in. length, is elongated under a pull to a length of 10.1 in., the total strain in the wire is: 10.1 − 10 = 0.1 *in.* Then *the unit strain* = *strain, in inches per inch of original length* = 0.1 ÷ 10 = 0.01.

218. Material Bodies Generally Tend To Resume Their Original Forms When Released From Forces Which Have Produced Strains In Them.—A rubber band may be stretched to a considerable length, but it will, apparently, instantly resume its original dimension when the stretching force is removed. Most materials, however, will not, when strained beyond certain limits, return entirely to their original shapes. In such cases the materials are said to have taken *permanent set*. Some materials acquire this condition under comparatively small loads. Others are permanently deformed only by application of very great loads.

219. Strains Are, Within Certain Limits, Directly Proportional To The Stresses From Which They Result.—That is to say, there is, usually (below the elastic limit, Sec. 220) for each substance, a definite ratio between a stress produced in the substance and the resulting deformation or strain. This ratio is called the *coefficient of elasticity* of the substance. See Table 221 for values. In the notation used in this book, the coefficient or elasticity will be denoted by E. Hence the formula:

$$E = \frac{stress}{strain} = \frac{lb.\ per\ sq.\ in.}{stretch\ per\ inch} \quad \text{(lb. per sq. in.)} \tag{102}$$

NOTE.—"MODULUS OF ELASTICITY" AND "YOUNG'S MODULUS" are synonymous terms for *coefficient of elasticity.*

EXAMPLE.—A steel rod, 20 in. long, when under a stress of 60,000 lb. per sq. in. stretches 0.04 in. What is the coefficient of elasticity of steel? SOLUTION.—By For. (102): $E = stress \div strain = lb.\ per\ sq.\ in. \div stretch\ per\ inch = 60{,}000 \div (0.04 \div 20) = 30{,}000{,}000$ *lb. per sq. in.*

EXAMPLE.—A bridge member of 0.5-sq. in. cross-section and 40-ft. length, elongates 0.25 in. under a certain load. If $E = 30{,}000{,}000$ lb. per sq. in, what is the load? SOLUTION.—By a transposition of For. (102): $Stress = E \times strain = lb.\ per\ sq.\ in. = E \times stretch\ per\ inch = 30{,}000{,}000 \times 0.25 \div (12 \times 40) = 15{,}625$ *lb. per sq. in.* Hence, the load $= 15{,}625 \times 0.5 = 7{,}813$ *lb.*

EXAMPLE.—The tension in a steel telephone-wire, 100 ft. long, is 525 lb. The cross-sectional area of the wire is 0.006,4 sq. in. $E = 30{,}000{,}000$ lb. per sq. in. How much has the wire stretched? SOLUTION.—By a transposition of For. 102: $Strain = stress \div E = stretch\ per\ inch = lb.\ per\ sq.\ in. \div E = (525 \div 0.006{,}4) \div 30{,}000{,}000 = 0.002{,}73$ *in.* Hence, the wire has stretched $0.002{,}73 \times 100 \times 12 = 3.28$ *in.*

220. When A Material Body Is Stressed Beyond A Certain Value Or "Limit," The Resulting Strain, Per Unit Of Load Increment, Becomes Greater Than Formerly.—The strain then ceases to be directly proportional to the stress (Sec. 219). When this limit is reached the ratio of *the stress in the body to the strain or deformation of the body* will be less than the similar ratio for stresses below this limit. The stress above which the strain ceases to be directly proportional to the stress, is called the *elastic limit* of the material. When a body is stressed beyond its elastic limit and the stress is then relieved (by removing the force which produced the stress), the body will be found to have suffered a permanent deformation. Stresses below the elastic limit do not cause any permanent deformation, or "set." Hence, when a stress is permitted to exceed the elastic limit, the body ceases to be truly "elastic" —that is, it ceases to be capable of returning to its former dimensions. Hence, the term "elastic limit" is truly significant. (See the author's STEAM BOILERS for graphs and a more complete discussion.)

NOTE.—THE "ULTIMATE STRENGTH" OF A MATERIAL is found by dividing the maximum force, which the material sustains during a test carried on until rupture occurs, by the original cross-sectional area of the test piece at the point of the rupture. In actual practice, the cross-sectional area usually changes before rupture occurs. Therefore, the maximum stress in the material may somewhat exceed the value of the "ultimate strength" which is computed as indicated above.

221. Table Showing Coefficients Of Elasticity For Different Materials.

Materials	*E* lb. per sq. in.	Materials	*E* lb. per sq. in.
METALS		WOODS	
Aluminum	11,000,000	Ash	1,600,000
Brass, cast	9,000,000	Birch	1,300,000
Brass wire	14,000,000	Oak	1,500,000
Phosphor bronze	14,000,000	Teak	2,410,000
Copper wire	16,000,000	Walnut	306,000
Iron, cast	12,000,000	Pine	1,900,000
Iron, wrought	27,000,000		
Lead	1,000,000	MISCELLANEOUS	
Tin, cast	4,000,000	Slate	14,000,000
Steel	30,000,000	Glass	8,000,000

222. Expansion And Contraction Of Restrained Solids will now be considered. If the tendency of a body of solid material to expand or contract is restrained in some manner, a stress will develop within the body. The result of such restraint will be the same as though the body were stressed by an external force. The stress produced by restraint of the tendency to expand or contract is exactly equal to the stress which would be set up in the body if it were, by some outside force, either elongated or compressed the amount which it tends to expand or contract.

Explanation.—Suppose a piece of copper is held tightly in a vise and is heated by means of a torch. Due to its absorption of the heat, the copper tends to expand, say, 0.01 in. But the clamping action of the jaws of the vise counteracts this tendency. Then the resultant condition within the piece of copper is the same as though the copper had first been heated and had then been squeezed or compressed 0.01 in. by a further tightening of the vise. By preventing the copper from responding to the expansion tendency produced by the heat, a compression stress, equal to that which would have been produced by compressing the copper 0.01 in., has been developed within the copper bar.

Note.—The Influence Of External Forces In Hindering Free Expansion And Contraction Of Structural Members Demands Close Attention.—Serious accidents may result from ignoring it. Bridge members may fail; see Figs. 180 and 181 for expansion joints. Dangerous stresses may be set up in steam boilers. Pavements may become distorted, or may even explode. Long pipe-coil radiators may buckle and leak and fittings in steam-piping systems may be strained and broken, unless proper arrangements which allow for expansion (Figs. 212 and 213) are provided.

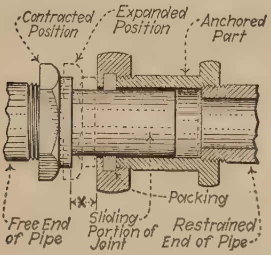


Fig. 212.—Expansion joint to allow pipe to expand.

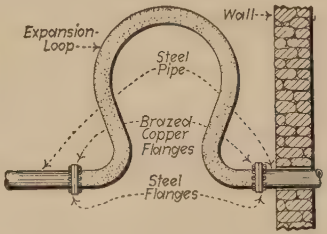


Fig. 213.—Expansion loop in high-pressure steam line.

223. When The Expansion Or Contraction Tendency Of A Solid Is Restrained Or Counteracted, A Strain Practically Proportional To The Coefficient Of Expansion Of The Material And To The Temperature Change Is Produced.—The piece of copper in the above explanation (Sec. 222) is compressed exactly the same amount that it would have expanded had it been free to do so. Hence, if the coefficients of expansion and elasticity of the material are known, and the temperature-change is observed, the stress, due to restrained expansion or contraction, in a solid may be calculated.

Explanation.—By referring to Fig. 197, it is evident that the expansion of an unconstrained bar of original length L_1 is $L_1 e_L T$, and its length after heating is $L_1(1 + e_L T)$. If, now, the bar is compressed to its original length, this expansion length $(L_1 e_L T)$ will be the amount of the total strain. Hence the unit strain will be: *(total strain)* ÷ *(length before straining)* $= L_1 e_L T \div L_1(1 + e_L T) = e_L T \div (1 + e_L T)$.

Now, the expansion coefficient e_L is so small that the term $e_L T$ seldom even approaches 1 per cent. Hence, it is ordinarily sufficient to say that the *unit strain* $= e_L T \div 1 = e_L T$, which is very nearly true.

Therefore, the strain is, as previously explained, practically proportional to the coefficient of expansion and the temperature change. Hence, the following equation may be written:

$$\frac{lb.\ per\ sq.\ in.\ stress}{unit\ strain} = \frac{lb.\ per\ sq.\ in.\ stress}{e_L T} \tag{103}$$

Wherein: e_L = coefficient of lineal expansion = expansion or contraction, in inches, per inch original length of body per degree Fahrenheit change in temperature. T = temperature change, in degrees Fahrenheit. But the first member of this equation gives (Sec. 219) the coefficient of elasticity. That is:

$$\frac{lb.\ per\ sq.\ in.\ stress}{unit\ strain} = E \qquad \text{(lb. per sq. in.)} \tag{104}$$

Hence, substituting (104) in (103):

$$E = \frac{lb.\ per\ sq.\ in.\ stress}{e_L T} \qquad \text{(lb. per sq. in.)} \tag{105}$$

Transposing (105) there results:

$$lb.\ per\ sq.\ in.\ stress = E e_L T \qquad \text{(lb. per sq. in.)} \tag{106}$$

Or, expressing the stress in terms of the equivalent restraining force, in pounds, and transposing, there results the following formula:

$$F = E e_L T A \qquad \text{(pounds)} \tag{107}$$

Wherein: F = the restraining force, in pounds. A = the cross-sectional area, in square inches, which offers resistance to the force.

Example.—In the explanation subjoined to Sec. 222, what compressive-force is exerted by the vise-jaws if the temperature of the copper is raised 200° F.?

Solution.—For copper, $e_L = 0.000{,}009{,}3$ and $E = 16{,}500{,}000$ lb. per sq. in. By For. (106), *stress* $= E e_L T = 16{,}500{,}000 \times 0.000{,}009{,}3 \times 200 = 30{,}690$ *lb. per sq. in.*

Example.—The joints of the steel rails in a street-car track are welded for a distance of 1,320 ft. The job is done on a summer day.

The temperature of the weather drops 35° F. during the following night. (1) What is the resulting tension in the rails if the ends cannot give? (2) How many inches will the track shorten if the ends are left free? SOLUTION.—For steel, $e_L = 0.000{,}006{,}5$ and $E = 30{,}000{,}000$ lb. per sq. in. (1) By *For.* (106), $stress = Ee_LT = 30{,}000{,}000 \times 0.000{,}006{,}5 \times 35 = 6{,}825$ lb. per sq. in. (2) By *For.* (94), $l = L_1e_LT = 1{,}320 \times 12 \times 0.000{,}006{,}5 \times 35 = 3.6$ *in.*

QUESTIONS ON DIVISION 7

1. Give some examples of materials expanding in length.

2. Give examples of peculiar constructions designed to allow for expansion.

3. What is a *coefficient of lineal expansion?* How may it be used?

4. State the formula for computing the length of a bar of material that has been heated a given amount.

5. What is *areal expansion?*

6. State and explain the formula for computing the area of a sheet of material that has been heated. Does this formula give an exact value? Why?

7. State and explain the formula for computing cubical expansion. Does this formula give an exact value? Why?

8. What is a *tensile stress?* A *compressive stress?*

9. In what units are tensile and compressive stresses expressed?

10. What is *shearing stress?*

11. What is meant by *stress? Strain?*

12. What is meant by the *coefficient of elasticity* of a material?

13. What is meant by *permanent set?*

14. State and explain the uses of coefficients of elasticity in computations relating to structural materials.

15. Why are openings left between the ends of the rails of railroad tracks? Why is tar placed in the joints of cement pavements?

16. If a metal body is so confined that it cannot expand, what is the result when it is heated?

17. Why should water in glass jars not be left out of doors in winter?

18. Why are the water-barrels which are placed on railroad bridges, for protection against fire, filled with salt-water?

19. State and explain the formula for computing the stress set up in a body wherein expansion or contraction is restrained.

20. Do the molecules of freezing water obey the general law which governs molecular action in substances from which heat is withdrawn? What is this law?

21. Why does ice float on water?

22. How do ice formations act to prevent lakes and rivers in cold latitudes from freezing to the bottom?

23. What causes the water to circulate in a hot-water heating system?

24. Why is antimony used in type metal?

25. Why would it be difficult to heat water if no convection currents were set up in the mass of water?

26. Why is it difficult to determine the coefficients of expansion of liquids?

27. Is the coefficient of expansion constant for each liquid?

28. Is there any difference in the cubical expansion of a liquid as compared with that of a solid?

29. What may happen if heat is applied to a vessel which encloses a liquid?

30. How is the shrinkage of iron castings compensated for in making the molds?

31. Are liquids compressible? What would be the probable effect of freezing water in a glass jar, if water were highly compressible?

32. When a boiler is cold, the water stands at a certain height in the gage glass. When the boiler is fired up, the water gradually rises to a higher level Why?

PROBLEMS ON DIVISION 7

1. A brass test-rod (*A*, Fig. 195) is 26.1 in. long at a temperature of 40° F. How long will it be when heated to 212° F.? What distance will the pointer move over the scale?

2 If a glass test-rod (*A*, Fig. 195) is inserted in the steam tube, what will be the expansion for the same temperature conditions as in Prob. 1?

3 A steel girder bridge (Fig. 180) is 98 ft. long. What distance will the movable shoe travel on the rollers when the temperature of the weather changes from 30° below 0° F. to 110° above 0° F.?

4. In bridge construction it is customary, if the length of the bridge is less than 50 ft., to fasten both ends rigidly. How much would a 50-ft. steel bridge, so secured, tend to expand lengthwise for each degree rise of temperature? If the bridge were set on piers, what would be the effect of this expansion tendency?

5. A long pipe line contains a series of expansion joints (Fig. 212). The joints are spaced 300 ft. apart. The line is designed to convey steam at a temperature of 300° F. It is erected in an atmospheric temperature of 50° F. In the adjustment of the joints, what should be the least distance, *X*, to allow for slip as the line expands?

6. A strip of concrete pavement is to be 30 ft. wide. It is to contain a series of expansion joints spaced at 100-ft. intervals. A temperature range of 100° F. is expected. Each expansion joint is to be 5 times as long as the maximum amount of lineal expansion occurring in each 100-ft. section of the pavement. What should be the length of each joint? How much will the surface area of a 100-ft. strip of pavement be increased by the expansion due to the anticipated range of temperature?

7. A concrete beam, reinforced with steel rods, is subjected to a bending load. A compressive stress is thus set up in one side of the beam while a tensile stress is set up in the opposite side. The tension is taken by the reinforcing rods. The coefficient of elasticity of the steel is 28,000,000 lb. per sq. in. If the rods are strained 0.000,1 in. per ft., what is the stress in them?

8. A bar of material is 0.3 sq. in. in cross-section and is 10 in. long. It elongates 0.002 in. when a load of 1,500 lb. is applied. Find the coefficient of elasticity.

9. A steel column is 12 sq. in. in cross-section and is 16 in. long It supports a load of 200,000 lb. How much is it compressed?

10. A line of steam pipe is 375 ft. long. Steel pipe having a coefficient of expansion of 0.000,006,3 is used. The cross-sectional area of the pipe is 2.5 sq. in. How much will the line expand under a temperature increase of 350° F.? If the line were so secured that it could neither stretch nor buckle under the increase of temperature, what force would be set up in it?

11. What is the amount of lineal expansion in a set of steel boiler tubes, 20 ft. long, when their temperature is raised from 50° F. to 600° F.? The area of cross-section of each tube is 1 sq. in. If cold water could be run into one of the tubes, thus cooling it to 200° F. while it is held rigidly at both ends and while the others remain at 600° F., what would be the probable stress set up in the cooled tube?

12. A hot-water heating system contains 500 gal. of water. The coefficient of expansion of water is 0.000,1. The water is heated from 50° F. to 210° F. If the boiler, pipes, and radiators of the system do not expand, what quantity of water will rise into the expansion tank?

DIVISION 8

HEAT PHENOMENA OF GASES

224. Heat Phenomena Of Gases (see note below) are of great practical importance because of their application to the various heat engines and heat processes with which the engineer must deal. While the laws, which will be given and explained in this division, will not in all cases apply directly to actual heat engines, the fundamental ideas which underlie them do apply. Hence, an understanding of these laws is essential. Before proceeding, however, the reader should review the matter in Secs. 96 to 108 on the molecular theory of gases.

225. A Gas Is Any Substance In The Gaseous State Which Closely Follows The General Gas Law.—The general gas law is stated and explained in following Sec. 249; for the present it need not be further considered. All gaseous substances as they depart further from the temperature and pressure conditions necessary to effect their liquefaction obey more closely this general gas law. Gaseous substances which are at or near their liquefaction conditions are called vapors and do not even approximately obey this general gas law. Hence it is apparent that it is the degree of departure of the conditions, under which a gaseous-state substance is existing, from its liquid-state conditions that determines whether it is a gas or a vapor. See note below.

NOTE.—THE DISTINCTION BETWEEN A GAS AND A VAPOR IS ONE OF DEGREE.—The early scientists gave the name "permanent gas" to such gaseous substances as they believed could not be liquefied—as, for example, air, hydrogen, oxygen, and nitrogen. More recent investigations have shown, however, that all of these substances can be liquefied when cooled to very low temperatures. Such substances, as water and ammonia, which need not be cooled to very low temperature, to be liquefied, were, by the earlier scientists, called vapors when in the gaseous state. These terms—"vapor" and "gas"—have been preserved, but their modern meanings are quite different from theirformer meanings.

Any substance, at least theoretically, may exist (in the gaseous state) as either a vapor or a gas. Vapors are further discussed in Div. 11. Since it is really the "nearness" of a gaseous substance to the liquid state that determines whether it is a vapor or a gas, it is obvious that there cannot be any rigid line of demarcation between the two. The transition from the vapor form to the gas form, or vice versa is not abrupt—it is gradual.

A vapor has been defined by some physicists as a substance in its gaseous state below its certical temperature (Sec. 349); and a gas as a substance in its gaseous state above its certical temperature. But these definitions are not, apparently, in accord with those of the best modern authorities.

226. The Laws Which Will Be Treated In This Division Apply With Absolute Accuracy Only To A Hypothetical "Perfect" Or "Ideal" Gas.—A *perfect gas* is one which, when heated or cooled, absorbs or gives up no disgregation heat (Sec. 258). No gas, so investigation shows, is, in this sense, a perfect gas. But many gases (air, oxygen, hydrogen, nitrogen and the like) are so nearly "perfect" that the errors, which will result from considering them as perfect in engineering computations, will be inconsequential. *Vapors* (Div. 11) on the other hand (such as slightly superheated or saturated steam, ammonia, carbon dioxide and sulphur dioxide) have characteristic properties such that the perfect-gas laws do not apply accurately to them.

NOTE.—IN DEALING WITH VAPORS, it is ordinarily necessary to use values which are taken from tables, as for example Steam Table 394. Such values are experimentally-determined ones. Steam and other vapors are treated in Div. 11.

227. The "Condition" Of a Gas—this is a technical term which is difficult to define—is determined by: (1) *The kind of gas;* that is, its chemical composition. (2) *The weight of the gas.* (3) *Its pressure.* (4) *Its volume.* (5) *Its temperature.* As will be shown, for a given gas, any three of the last four of the above items determine the unknown properties. Whenever any of these properties of a gas are altered, the gas is said to undergo a *change in condition or a condition change.* It will be shown in this division, how changes in one or more of the above properties of a gas affect its remaining properties. It will also be shown how condition changes are affected by heat transfer and external work.

Example.—If a quantity of a gas (Sec. 225) such as air, hydrogen or nitrogen is compressed (Fig. 214) in a closed vessel, its volume will (as the impressed pressure is increased) readily decrease (Fig. 215), in proportion to the applied pressure. Or, if the pressure is decreased (Fig. 216), the body of gas will expand correspondingly and fill the larger space. In compressing the gas (Fig. 215), the falling weight does external work on it. All of this work (assuming a frictionless piston and no loss of heat) is converted into heat in the compressed gas. Thereby the temperature of the gas is increased. When the gas is permitted to expand (Fig. 216), it does work in raising the weight. Its heat content and temperature are thereby decreased accordingly.

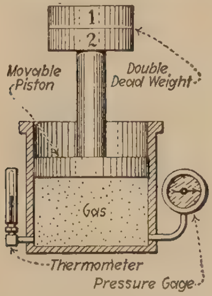


Fig. 214.—Illustrating the compression of a gas. As the weights 1 and 2 are placed on the rod, the gas is compressed.

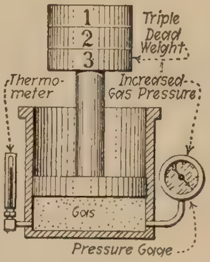


Fig. 215.—Illustrating the effect of increased compression due to addition of third weight.

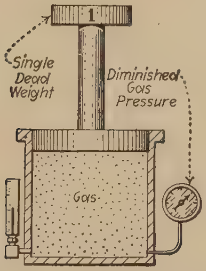


Fig. 216.—Illustrating the effect of diminished compression due to removing weight.

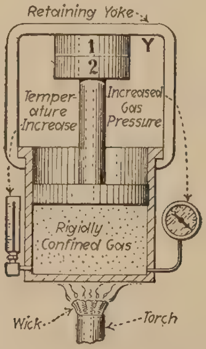


Fig. 217.—Illustrating increase of pressure by heating. (Compare with Fig. 214.)

Now, if heat be applied to the vessel (Fig. 217) and the piston is restrained by yoke, *Y*, from upward movement, the pressure exerted by the gas will increase. The added heat (energy) causes an increase in the molecular vibration (Sec. 52) which produces the increased pressure. If (Fig. 218) there is no restraining yoke, the pressure of the gas must, as it is heated, remain constant (until *P* is pushed from the cylinder) but the volume of the gas will increase: Obviously heat energy derived from the torch flame (Fig. 218) is converted into mechanical energy which does work in raising the weights.

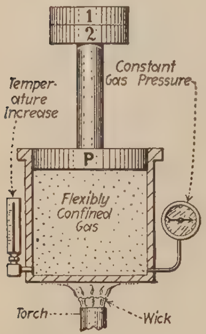


Fig. 218.—Illustrating increase of volume by heating. (Compare with Fig. 214.)

The above-described—and other—gas-condition changes occur in conformity with certain definite laws. It is proposed to consider these laws in succeeding sections.

228. Physical Gas Phenomena Will First Be Considered Without Reference To Energy Or Work Transfer Or Changes. That is, before proceeding with the energy relations for gas expansion and contraction, the following laws and subjects will be discussed: (1) *Boyle's law*, Sec. 230. (2) *Charles' law*, Sec. 237. (3) *Gay-Lussac's law*, Sec. 240. (4) *General gas law*, Sec. 248. (5) *Gas densities*, Sec. 253. (6) *Draft produced by differences in gas density*, Sec. 256. It is desirable that these laws and subjects be thoroughly understood before the reader studies the energy and work relations which apply in the expansion and contraction of gases.

229. Certain Laws Which Follow Relate To Changes Wherein Some Property Such As Temperature, Volume Or Pressure Remains "Constant."—This does not mean that necessarily the property must actually remain the same during the whole while that the change is occurring in order that the law may apply. The laws will apply not only when the "constant" condition is not varied while the change is occurring but they will also apply when after a change, the "constant" property is restored to its original value.

Example.—Boyle's law which follows applies only when the gas temperature is maintained "constant." But the law is effective in computing the volume or pressure for a second condition if the volume and pressure for the first condition are known, provided the gas temperature for the second condition is restored to its original value, although gas temperature changes may have occurred in the meantime.

230. Boyle's Law, first stated by the Irish physicist, Robert Boyle, who discovered it experimentally, is: *If the temperature of a given weight of gas is kept constant* (Fig. 219), *the absolute pressure of the gas will vary inversely as its volume;* conversely,

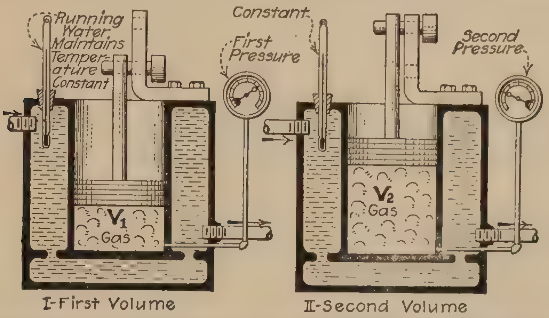


FIG. 219.—Boyle's law—temperature of a given weight of gas kept constant—pressure varies inversely as the volume. (Running water maintains gas temperature constant.) The pin holds the piston in fixed positions. In *II* the volume is twice that of *I* hence the pressure in *II* is ½ that in *I*.

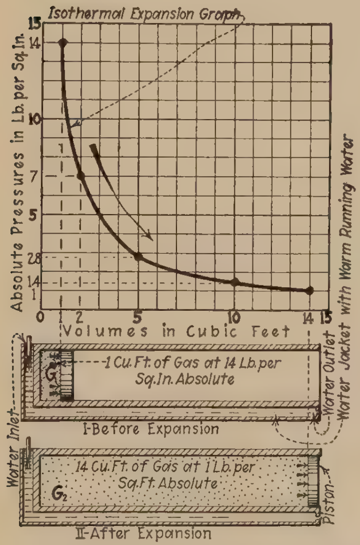


FIG. 220.—Gas expansion in accordance with Boyle's law. (Temperature maintained constant through heating effect of water jacket.)

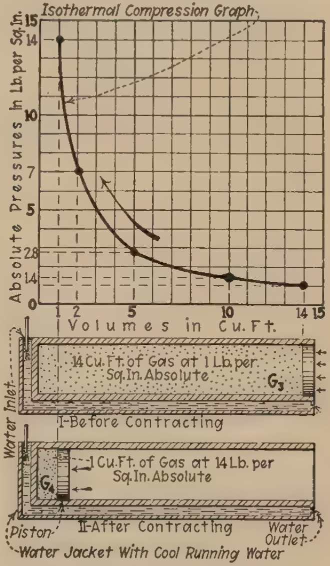


FIG. 221.—Gas compression in accordance with Boyle's law. (Constant temperature maintained through cooling effect of jacket-water.)

the volume will vary inversely as the absolute pressure. Note particularly that this law applies only when the gas temperature is maintained constant (see Sec. 229). That is, it applies only for *isothermal* (constant temperature) *changes* (Sec. 271). The law means (Figs. 220 and 221) that with a given weight of gas, if the volume of the gas is doubled. its absolute pressure will be halved, if its volume is tripled, its absolute pressure will then be one third of the original pressure, and so on.

231. The Problems To Which Boyle's Law May Be Applied are those wherein the *volume* of a *given weight* of a gas at a *certain pressure* is known and it is desired to compute the *volume* of the gas at a different *pressure*, or the *pressure* exerted by the gas when it occupies a different *volume*, the gas *temperature being the same* for the second condition as for the first. In practice, it is regarded more convenient by some persons to apply the general gas law of For. (145) for the solution of these problems.

232. The Boyle's-law Formula, which follows directly from the verbal statement of the law, is:

$$\frac{P_1}{P_2} = \frac{V_2}{V_1} \qquad \text{(108)} \quad \text{(ratio)}$$

Wherein: P_1 and P_2 = respectively, the initial and final absolute pressures of any given weight of gas at a constant temperature (Sec. 229) in any pressure unit whatsoever, but both must be in the same unit. V_1 and V_2 = respectively, the initial and final volumes of the gas, in any volume unit whatsoever, but both must be in the same unit.

NOTE.—IT IS IMPORTANT TO NOTE THAT IN ANY PROBLEM WHICH INVOLVES INITIAL AND FINAL CONDITIONS OF GASES, EITHER CONDITION MAY BE CONSIDERED THE INITIAL AND EITHER THE FINAL CONDITION.—Thus, in applying Boyle's law, if there is a known value for P_2, and P_1 is desired, then P_2 may be considered the initial and P_1 the final pressure. The same numeral subscript always refers to one set of conditions existing at the same time and must not be confused. That is, P_2 always refers to the pressure at a volume of V_2 and a temperature (see following sections) of T_2. All the gas changes considered in this division, however, are reversible (Sec. 154) and may be thought of as taking place in either direction.

Note.—Transposed Forms Of Boyle's Law, which are useful in solving problems, are here given:

$$P_2 = \frac{P_1V_1}{V_2} \qquad \text{(final absolute pressure)} \tag{109}$$

$$V_2 = \frac{P_1V_1}{P_2} \qquad \text{(final volume)} \tag{110}$$

Wherein all symbols have the same meanings as stated under For. (108).

Example.—A certain weight of gas is compressed into a steel cylinder of a volume of 0.2 cu. ft. (V_1, Fig. 222) and then exerts a pressure of 200 lb. per sq. in. gage. What will be the volume of this gas at atmospheric pressure (0 lb. per sq. in. gage) when the temperature in V_2 is the original temperature in V_1? Solution.—By For. (110), $V_2 = P_1V_1/P_2 = (200 + 14.7) \times 0.2 \div (0 + 14.7) = 2.92$ *cu. ft.*

Example.—A certain gas container has in it 54,300 cu. ft. of a gas when the barometer registers 29.12 in. of mercury column. Only atmospheric pressure is imposed on the gas in the container. Without leakage and without temperature change, it is found that the volume of the gas in the container increases to 54,650 cu. ft. What is the barometric pressure for the larger volume? Solution.—Barometers measure absolute pressures. Substitute in For. (109): $P_2 = P_1V_1/V_2 = 29.12 \times 54{,}300 \div 54{,}650 = 28.93$ *in. mercury column.*

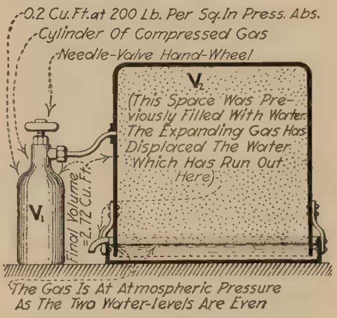

0.2 Cu.Ft.at 200 Lb. Per Sq.In Press. Abs.
Cylinder Of Compressed Gas
Needle-Valve Hand-Wheel
V2
(This Space Was Previously Filled With Water. The Expanding Gas Has Displaced The Water Which Has Run Out Here)
V1
Final Volume =2.72 Cu.Ft.
The Gas Is At Atmospheric Pressure As The Two Water-levels Are Even

Fig. 222.—Certain weight of a gas, compressed to a volume, V_1, of 0.2 cu. ft. at 200 lb. per sq. in. gage pressure. What will be its volume, V_2, at atmospheric pressure? Temperature remains constant.

233. For A Given Weight Of Gas At A Constant Temperature, The Product Of The Absolute Pressure And The Volume Will Be Constant regardless of the pressure and corresponding volume and vice versa. This is therefore the governing relationship for isothermal changes (Sec. 271). This is merely another statement of *Boyle's law* because by transposing For. (108), there results:

$$P_1V_1 = P_2V_2 = P_3V_3 \text{ etc} \qquad \text{(a constant)} \tag{111}$$

or this may be written:

$$PV = k \qquad \text{(a constant)} \tag{112}$$

Explanation.—A cylinder (Fig. 223) with a movable piston head, P, contains 2 cu. ft. of gas at an absolute pressure of 30 lb. per sq. in.

For this condition, *pressure* × *volume* = $PV = 30 \times 2 = 60$. Now weights, W (Fig. 224), are added to the movable head until the volume of the gas is compressed to 1 cu. ft. (The cylinder is so surrounded with running water that it carries away the heat generated by the compression and maintains the temperature of G constant.) By the addition of the weights the pressure will be increased to (For. 109) 60 lb. per sq. in. abs. But $PV = 1 \times 60 = 60$ as before. For any other pressure and volume, their product would be 60. Furthermore, it will be noted from Figs. 220 and 221, that the product of P and V for any point on either of these Boyle's-law graphs is a constant. Thus: $14 \times 1 = 14$; $7 \times 2 = 14$; $2.8 \times 5 = 14$; $1.4 \times 10 = 14$; $1 \times 14 = 14$. It obviously follows then that:

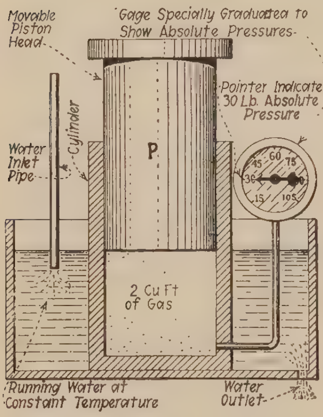

Movable Piston Head
Gage Specially Graduated to Show Absolute Pressures
Pointer Indicates 30 Lb. Absolute Pressure
Cylinder
Water Inlet Pipe
P
2 Cu Ft of Gas
15
30
45
60
75
105
Running Water at Constant Temperature
Water Outlet

Fig. 223.—Illustrating Boyle's law, 2 cu. ft., at 30 lb. per sq. in. abs. pressure.

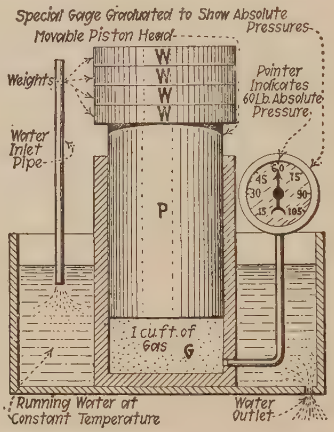

Special Gage Graduated to Show Absolute Pressures
Movable Piston Head
Weights
W
W
W
W
Pointer Indicates 60 Lb. Absolute Pressure
Water Inlet Pipe
P
15
30
45
60
75
90
105
1 cu. ft. of Gas
G
Running Water at Constant Temperature
Water Outlet

Fig. 224.—Illustrating Boyle's law, 1 cu. ft. at 6 lb. per sq. in. abs. pressure.

$$P_1V_1 = P_2V_2 = P_3V_3 \ldots\ldots\ldots\ldots, \text{etc.} = k \quad \text{(a constant)} \tag{113}$$

which is the statement of For. (112) above.

234. The Pressure-temperature Changes At Constant Volume for a given weight of any certain gas were early investigated (see note under Sec. 237) and found to follow a general law (to be here called Charles' law): *If a given weight of any gas is confined in a fixed volume and its pressure is measured while the gas is at 32° F., it will be found that its absolute pressure will increase* $\frac{1}{492}$ *for each* 1° *F. that its temperature is increased* —or, *its absolute pressure will decrease* $\frac{1}{492}$ *for each* 1° *F.*

that its temperature is decreased. This relation may be written as a formula, thus:

(114) $P_T = P_{32}[1 + \frac{1}{492}(T - 32)]$ (abs. pressure)

or, expressing "$\frac{1}{492}$" as a decimal:

(115) $P_T = P_{32}[1 + 0.002{,}033\ (T - 32)]$ (abs. pressure)

Wherein: P_T = the absolute pressure of a gas, in any unit of pressure, at a certain temperature, T, and in a certain volume V. P_{32} = the absolute pressure of the same gas, in the same units as P_T is measured, when in the same volume, V, and at 32° F. T = the temperature of the gas when exerting the pressure, P_T, in degrees Fahrenheit.

EXAMPLE.—A certain weight of gas, when confined in a closed container at 32° F., exerts a pressure of 100 lb. per sq. in. abs. Now at 33° F. and in the same volume, its pressure will be $\frac{1}{492} \times 100 = 0.203{,}3$ lb. per sq. in. greater than at 32° F. Furthermore, at 42° F. its pressure will be $10 \times 0.203{,}3 = 2.033$ lb. per sq. in. greater than at 32° F. These same results may have been found by using For. (115), thus: At 33° F., $P_T = P_{32}[1 + 0.002{,}033(T - 32)] = 100[1 + 0.002{,}033(33 - 32)] = 100(1 + 0.002{,}033) = 100.203{,}3$ *lb. per sq. in. abs.* Likewise at 42° F., $P_T = 100[1 + 0.002{,}033(42 - 32) = 100(1 + 0.020{,}33) = 102.033$ *lb. per sq. in. abs.*

EXAMPLE.—A cubic foot of air at 32° F. is under pressure of 300 lb. per sq. in. abs. What would be the pressure if the air were cooled in the same volume to 0° F.? SOLUTION.—By For. (115), $P_T = P_{32}[1 + 0.002{,}033(T - 32) = 300[1 + 0.002{,}033(0 - 32)] = 300\ (1 - 0.065) = 280.5$ *lb. per sq. in. abs.*

235. The Volume-temperature Changes At Constant Pressure for a given weight of any gas were also investigated (see note under Sec. 237) and found to follow a similar law to that given in the preceding section. The law governing the volume-temperature changes at constant pressure for a given weight of a gas is to be here called Gay Lussac's law: *If a given weight of any gas be so confined that its volume and temperature can be varied while its pressure remains constant, it is found that the volume increases $\frac{1}{492}$ of the volume at 32° F. for each 1° F. increase in its temperature; likewise the volume of the gas decreases $\frac{1}{492}$ of its volume at 32° F. for every 1° F. decrease in temperature.* This relation may be written as a formula, thus:

(116) $V_T = V_{32}[1 + \frac{1}{492}\ (T - 32)]$ (volume)

or, expressing "1/492" as a decimal:

(117) $$V_T = V_{32}[1 + 0.002{,}033(T - 32)] \qquad \text{(volume)}$$

Wherein: V_T = the volume of a given weight of gas (in any unit) at a certain temperature, T, and pressure P. V_{32} = the volume of the same gas when at 32° F. and under the same pressure P. T = the temperature, in degrees Fahrenheit, at which the gas occupies the volume V_T.

Example.—If at 32° F. and at atmospheric pressure a certain weight of a gas occupies 2 cu. ft., what volume will that same gas occupy at 50° F., at 800° F., and at −20° F., the pressure being in each case that of the atmosphere? Solution.—By For. (117), $V_T = V_{32}[1 + 0.002{,}033(T - 32)]$. Hence, at 50° F., $V_T = 2[1 + 0.002{,}033(50 - 32)] = 2(1 + 0.036{,}6) = 2.073{,}2$ *cu. ft.* At 800° F., $V_T = 2[1 + 0.002{,}033(800 - 32)] = 2(1 + 1.561) = 5.132$ *cu. ft.* At −20° F., $V_T = 2[1 + 0.002{,}033(-20 - 32)] = 2(1 - 0.105{,}7) = 1.788{,}6$ *cu. ft.*

236. Our Notion Or Concept Of Absolute Temperature is based on the laws of Charles and Gay Lussac, as given in Secs. 234 and 235. If an attempt is made, by using For. (114), to find the pressure exerted by any gas at the temperature of −460° F., it is evident that the resulting pressure is zero. Likewise, cooling a gas at constant pressure to −460° F., will, by For. (116), reduce its volume to zero. Hence, if any (perfect) gas followed these laws exactly and if it were possible to cool the gas gradually to a lower and lower temperature, it would be found that, at −460° F., the gas would occupy no volume and would exert no pressure on the wall of its containing vessel. Therefore, it is logical to assume that no lower temperature than −460° F. can ever be attained for, if a lower temperature could be attained, then the volume of a gas would, by For. (116), become negative—which is inconceivable. Hence, −460 F. is called the *absolute zero of temperature* and temperatures measured from −460° F. as a starting or datum point are called *absolute temperature* (see also Sec. 61). As a formula:

(118) $$\mathbf{T} = T + 460 \qquad \text{(deg. fahr. abs.)}$$

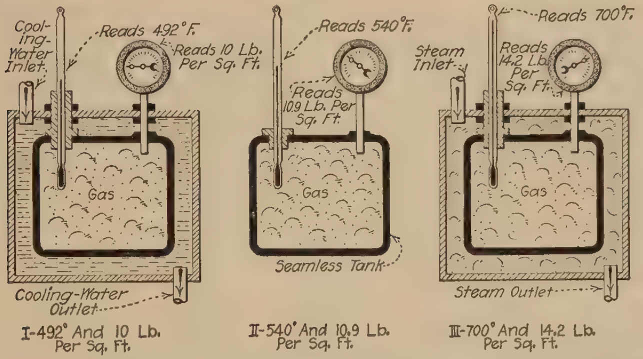
or, transposing:

(119) $$T = \mathbf{T} - 460 \qquad \text{(deg. fahr.)}$$

Wherein: T = the temperature of any body, in degrees

Fahrenheit on the *absolute scale.* T = the temperature of the body in degrees Fahrenheit on the *Fahrenheit scale.*

EXAMPLE.—See examples under Sec. 62.



I-492° And 10 Lb. Per Sq. Ft. II-540° And 10.9 Lb. Per Sq. Ft. III-700° And 14.2 Lb. Per Sq. Ft.

FIG. 225.—Illustrating Charles' law. With a constant volume of a given weight of gas, the absolute pressure varies as the absolute temperature. (See following graph for points corresponding to *I*, *II*, and *III* above.)

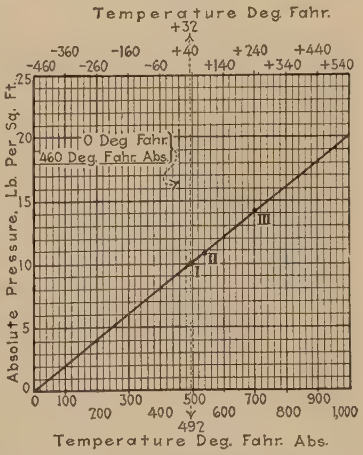


FIG. 226.—Graph illustrating Charles' law. Shows variations of pressure with temperature, of any given weight of a perfect gas, which is maintained at constant volume and which exerts a pressure of 10 lb. per sq. ft. at 32° F.

237. Charles' Law may be stated thus: *If the volume of a given weight of gas* (Fig. 225) *is kept constant, the absolute pressure will vary directly as the absolute temperature of the gas.* Note particularly that this law applies only when the volume of the gas is maintained constant (see Sec. 229). That is, it applies only for *isometric* (constant volume) *changes* (Sec. 269). This law means that, with the volume held constant, if the absolute temperature of a given weight of a gas is doubled, its absolute pressure will be doubled; if its absolute temperature is tripled, its absolute pressure will be tripled and so on. Likewise, halving the absolute temperature halves the pressure, etc. Figure 226 illustrates this fact graphically. See Sec. 239 for proof that the above statements are the same as those of Sec. 234.

NOTE.—CHARLES' LAW AS JUST ABOVE STATED IS ALSO SOMETIMES CALLED DALTON'S LAW OR GAY LUSSAC'S LAW. (This should not be confused with Dalton's laws of mixed-gas partial pressures Sec. 306, which is an entirely different thing.) "Dalton in 1801 first published the law. Gay Lussac, independently of Dalton, published the law in 1802. In his publication, Gay Lussac states that Charles in 1787 had noted the law but had never published it." (Stone's EXPERIMENTAL PHYSICS, p. 92, *Ginn & Co.*, 1897). The above "Charles' law" and the following "Gay Lussac's law" are together often referred to variously by different writers as either Charles' law or Gay Lussac's law. But for the purposes of this book, it is deemed wiser to adopt the nomenclature which is indicated.

238. The Problems To Which Charles' Law May Be Applied are those wherein the pressure of a given weight of gas, which is maintained at a constant volume, is known for a certain temperature and it is desired to compute either the pressure exerted by the gas at a different temperature or the temperature necessary to produce a different pressure. In practice, it is regarded as more convenient, by some people, to apply the *general gas law*, For. (145), for solving these problems.

NOTE.—THE ONLY CHANGES TO WHICH CHARLES' LAW APPLIES ARE THOSE WHICH ARE CAUSED BY THE ADDITION OR SUBTRACTION OF HEAT, whereby the gas temperature is varied. The law cannot, since it is true only for *a given weight of gas at constant volume*, hold for changes caused by adding or subtracting gas or by compressing or expanding it.

239. The Charles'-law Formula which expresses the relationship as given in the statement of the law (Sec. 237) is:

(120) $$\frac{P_1}{P_2} = \frac{\mathrm{T}_1}{\mathrm{T}_2}$$ (ratio)

or,

(121) $$P_2 = \frac{P_1\mathrm{T}_2}{\mathrm{T}_1}$$ (final pressure)

or,

(122) $$\mathrm{T}_2 = \frac{\mathrm{T}_1 P_2}{P_1}$$ (final temperature)

Wherein: P_1 and P_2 = respectively the initial and final absolute pressures of any given weight of gas at constant volume, which may be expressed in any pressure unit but boht must be expressed in the same unit. $\mathbf{T}_1$ and $\mathbf{T}_2$ = respectively the initial and final absolute temperatures of the gas expressed in any temperature unit provided both are expressed in the same unit.

Derivation.—By For. (114): $P_T = P_{32}[1 + \frac{1}{492}(T - 32)]$. By For. (119): $T = \mathbf{T} - 460$. Now, substituting for T in For. (114), there results:

$$P_T = P_{32}\left\{1 + \frac{1}{492}\left[(\mathbf{T} - 460) - 32\right]\right\} \tag{123}$$

Simplifying, there results:

$$P_T = P_{32}\left[1 + \frac{1}{492}(\mathbf{T} - 492)\right] \tag{124}$$

$$P_T = P_{32}\left[1 + \frac{\mathbf{T}}{492} - \frac{492}{492}\right] \tag{125}$$

$$P_T = P_{32}\left[1 + \frac{\mathbf{T}}{492} - 1\right] \tag{126}$$

$$P_T = P_{32} \times \frac{\mathbf{T}}{492} \tag{127}$$

$$\frac{P_T}{P_{32}} = \frac{\mathbf{T}}{492} \tag{128}$$

Now, 32° F. = 492° F. abs. Hence, by using the symbols of For. (120), For. (128) becomes:

$$\frac{P_1}{P_2} = \frac{\mathbf{T}_1}{\mathbf{T}_2} \tag{129}$$

which is the same as For. (120).

Example.—If the pressure of a certain weight of gas, the volume of which is maintained constant, is 100 lb. per sq. in. absolute and its temperature is 300° F. abs., what increase in temperature is necessary to increase the pressure exerted by this weight of gas to 150 lb. per sq. in. abs.? Solution.—By For. (122), $\mathbf{T}_2 = \mathbf{T}_1 P_2/P_1 = 300 \times 150 \div 100 =$ *450° F. abs.* This represents a temperature increase of $450 - 300 =$ *150° F.*

Example.—The gage on an airtight compressed-air tank (constant volume) registers 115 lb. per sq. in. The air in it has been heated by compression to 150° F. What will the gage register when the air cools down to 70° F.? Solution.—By For. (121), $P_2 = P_1\mathbf{T}_2/\mathbf{T}_1 = (115 + 14.7) \times (70 + 460) \div (150 + 460) =$ *112.7 lb. per sq. in. abs.*; or $112.7 - 14.7 =$ *98.0 lb. per sq. in. gage.*

Example.—Say that 200 lb. per sq. in. is considered a safe gage pressure for a certain gas-storage tank (constant volume). Gas is pumped into the tank at a temperature of 49° F. until the pressure in the tank is 175 lb. per sq. in. gage. If the valves are all closed when the tank is full of gas in this condition, what will be the highest safe temperature to which the tank may be subjected? Solution.—By

For. (122), $T_2 = T_1P_2/P_1 = (49 + 460) \times (200 + 14.7) \div (175 + 14.7) = 576°$ *F. abs.*; or $576 - 460 = 116°$ *F.*

240. Gay Lussac's Law may be stated thus: (Fig. 227): *If the absolute pressure of (imposed on) a given weight of any gas is kept constant, its volume will vary directly as the absolute temperature of the gas.* Note the similarity between this and Charles' law of Sec. 237; with Charles' law the volume is kept constant and the pressure varies while with Gay Lussac's law the pressure is kept constant and the volume varies. Also note particularly that *Gay Lussac's law applies only* when the pressure of, that is the pressure imposed on, the gas is maintained constant. That is, Gay Lussac's law applies only for *isobaric* (constant-pressure) *changes* (Sec. 270). This law means (Figs. 228 and 229) that, with the pressure held constant, if the absolute temperature of a given weight of gas is doubled, its volume will be doubled; if its absolute temperature is tripled, its volume will be tripled and so on.

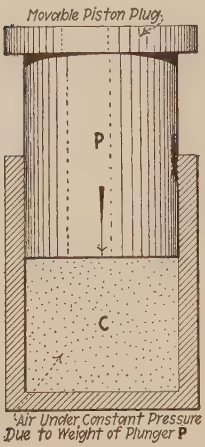
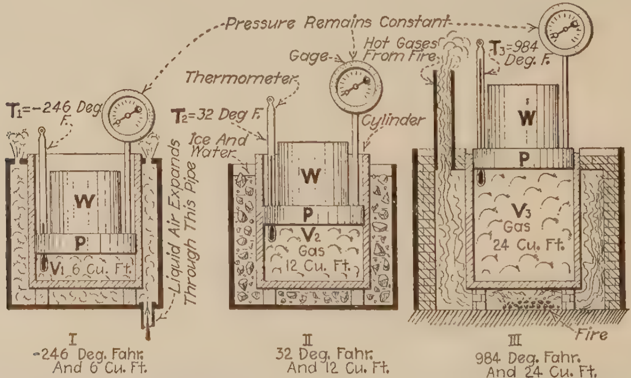


FIG. 227.—Air confined under constant pressure. (Since the weight of the perfectly-fitting frictionless piston plug and that of atmospheric pressure if any, are constant, the pressure imposed on and hence exerted by the air must be constant.)



I
-246 Deg. Fahr. And 6 Cu. Ft.

II
32 Deg. Fahr. And 12 Cu. Ft.

III
984 Deg. Fahr. And 24 Cu. Ft.

FIG. 228.—Diagram illustrating Gay Lussac's law. (With a given weight of gas at constant pressure, the volume varies as the absolute temperature, See following graph for points corresponding to *I*, *II*, and *III*, above.)

Likewise, halving the absolute temperature halves the volume; with $\frac{1}{3}$ the original absolute temperature the volume will be $\frac{1}{3}$ of the original volume, etc.

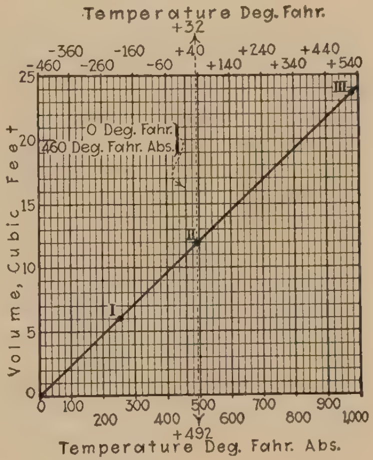


Fig. 229.—Graph illustrates Gay Lussac's law. Shows variation of volume directly with temperature, of any given weight of a perfect gas which is maintained at constant pressure and which occupies a volume of 12 cu. ft. at 32° F.

241. The Problems To Which Gay Lussac's Law May Be Applied are those wherein the volume of a given weight of gas, which is maintained at a constant pressure is known for a certain temperature and it is desired to compute either the volume of the gas at a different temperature or the temperature necessary to produce a different volume. Note that, in practice, it is usually more convenient to apply the *general gas law*, For. (145) for solving these problems.

Note.—The Only Changes To Which Gay Lussac's Law Applies Are Those Which Are Caused By The Addition Or Subtraction Of Heat, whereby the gas temperature is varied. The law cannot, since it is true only for *a given weight of gas at constant pressure*, hold for changes caused by adding or subtracting gas or for changes by compressing or expanding it mechanically unless heat is simultaneously abstracted or added at just the proper rates to maintain the pressure constant.

242. The Gay Lussac's-law Formula, which expresses mathematically the preceding verbal statement of the law, is:

$$\frac{V_1}{V_2} = \frac{\mathrm{T}_1}{\mathrm{T}_2} \tag{130}$$ (ratio)

or,

$$V_2 = \frac{V_1 \mathrm{T}_2}{\mathrm{T}_1} \tag{131}$$ (final volume)

or,

$$\mathrm{T}_2 = \frac{\mathrm{T}_1 V_2}{V_1} \tag{132}$$ (final temp.)

Wherein: V_1 and V_2 = respectively the initial and the final volumes of the gas which may be expressed in any unit of volume, but both must be expressed in the same unit. $\mathbf{T}_1$ and $\mathbf{T}_2$ = respectively the initial and final absolute temperatures of the gas expressed in any temperature unit provided both are expressed in the same unit.

Derivation.—The formula given above (130), can be derived from For. (116) just as was For. (120) derived from For. (114) in Sec. 239.

Example.—A given weight of a gas is confined at atmospheric pressure and occupies 75 cu. ft. at 520° F. abs. What volume will it occupy at 635° F. abs. and at the same pressure? Solution.—By For. (131), $V_2 = V_1\mathbf{T}_2/\mathbf{T}_1 = 75 \times 635 \div 520 = 91.6$ *cu. ft.*

Example.—A body of gas at 580° F. abs. is compressed to one third of its original volume. To what temperature must it be cooled to reduce its pressure to the same value as that before the compression? Solution.—By For. (132), $\mathbf{T}_2 = \mathbf{T}_1V_2/V_1 = 580 \times 1 \div 3 = 193°$ *F. abs.*

Example.—If a certain weight of a flexibly confined gas (Fig. 230), which is maintained at constant pressure has a volume of 9 cu. ft. at 32° F., what will be its volume when the gas is heated to 52°? What would be its volume if the gas were cooled to 22° F.? Solution.—By For. (118), $\mathbf{T} = T + 460$. Hence $\mathbf{T}_1$, (32° F.) = 32 + 460 = 492° *F. abs.* Also, $\mathbf{T}_2$ (52° F.) = 52 + 460 = 512° *F. abs.* And, $\mathbf{T}_3$ (22° F.) = 22 + 460 = 482° *F. abs.* By For. (131), $V_2 = V_1\,\mathbf{T}_2/\mathbf{T}_1 = 9 \times 512 \div 492 = 9.37$ *cu. ft.* Also, $V_3 = V_1\mathbf{T}_3/\mathbf{T}_1 = 9 \times 482 \div 492 = 8.8$ *cu. ft.*

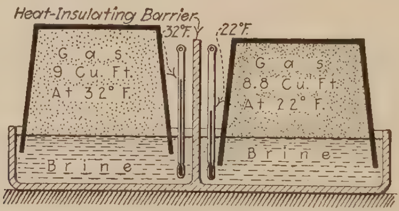


Fig. 230.—Showing decrease in volume at constant pressure due to 10° F. decrease in temperature.

Example.—If 100 cu. ft. of air at 60° F. is drawn into a boiler furnace, what volume will this air occupy: (*a*) In the combustion chamber where the temperature is 2,350° F.? (*b*) In the last pass of the boiler where the temperature is 500° F.? (*c*) In the stack where the temperature is 250° F.? The pressure of the flue gases is, practically, atmospheric pressure in all parts of a furnace, boiler, and stack. Hence, the pressure may be assumed to be constant in this example.

Solution.—By For. (118), $\mathbf{T} = T + 460$. Hence, $\mathbf{T}_1$ (60° F.) = 60 + 460 = 520° *F.* abs. Also, $\mathbf{T}_2$ (2,350° F.) = 2,350 + 460 = 2,810° *F. abs.*

and T_3 (500° F.) = 500 + 460 = 960° *F. abs.* and T_4 (250° F.) = 250 + 460 = 710° *F. abs.* (*a*) By For. (131), $V_2 = V_1T_2/T_1 = 100 \times 2{,}810 \div 520 = 540$ *cu. ft.* (*b*) Also, $V_3 = V_1T_3/T_1 = 100 \times 960 \div 520 = 185$ *cu. ft.* (*c*) And, $V_4 = V_1T_4/T_1 = 100 \times 710 \div 520 = 137$ *cu. ft.*

243. A Combination Of Two Of The Three Fundamental Laws (Boyle's, Charles' And Gay Lussac's) May Be Employed To Determine The Effect Of Simultaneous Changes In Volume, Pressure, And Temperature, for a given weight of any gas, when values for all three of these properties are known for the initial condition and values for two of them are known for the final condition. (See Table 244.) *First,* to find the result due to the changes in two of the properties, one of the laws is employed. *Then,* one other of the laws is applied (using the value obtained in the first operation) to compute the effect of the change in the third property. In any case, the two formulas which are used are the ones in both of which the unknown quantity (V, P, or T) appears. The following example explains the operation.

Note.—For. (133) Which Combines In One Boyle's, Charles', And Gay Lussac's Laws, May Be Used Instead Of The Above Explained Operation.—Or, in practice, the general gas law, Sec. 249, which is usually more convenient and which is of broader application is, ordinarily, employed. The material in the preceding and following sections is included principally to permit of a logical development of the general gas law of following Sec. 249.

244. Table Showing Combined Applications Of Boyle's, Charles', And Gay Lussac's Laws.—See Sec. 243 (This applies only *for a given weight* of any gas).

GIVEN		TO FIND	Use these laws:	Formulas for the laws:
Initial	Final			
V_1 = Volume P_1 = Pressure $\mathbf{T}_1$ = Temperature	P_2 = Pressure $\mathbf{T}_2$ = Temperature	V_2 = Volume	Boyle's. Gay Lussac's.	$V_2' = \frac{V_1P_1}{P_2}$, $V_2 = \frac{V_2'\mathbf{T}_2}{\mathbf{T}_1}$
	V_2 = Volume $\mathbf{T}_2$ = Temperature	P_2 = Pressure	Boyles'. Charles'.	$P_2' = \frac{V_1P_1}{V_2}$, $P_2 = \frac{P_2'\mathbf{T}_2}{\mathbf{T}_1}$
	V_2 = Volume P_2 = Pressure	$\mathbf{T}_2$ = Temperature	Charles'. Gay Lussac's.	$\mathbf{T}_2' = \frac{\mathbf{T}_1P_2}{P_1}$, $\mathbf{T}_2 = \frac{\mathbf{T}_2'V_2}{V_1}$

$\mathbf{T}$ = Absolute temperature in the above table.

EXAMPLE.—A cylinder (Fig. 231) contains 1 cu. ft. of gas at an absolute pressure of 15 lb. per sq. in., and temperature of 500° F. abs. Now, the absolute pressure is increased (Fig. 232) to 30 lb. per sq. in. Then, the temperature is increased (Fig. 233) to 600° F. abs. What is the resulting volume? (The final result would be the same if the above-specified changes all occurred simultaneously instead of occurring one after the other.)

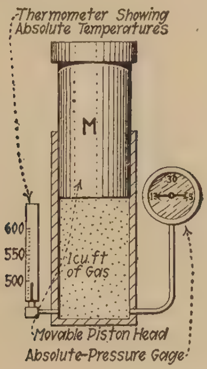


FIG. 231.—Illustrating the initial condition of the gas in the example.

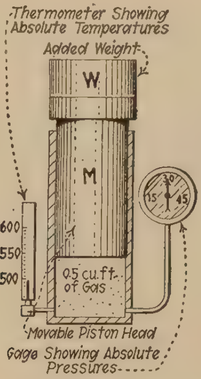

Thermometer Showing Absolute Temperatures
Added Weight
W
M
30
15
45
600
550
500
0.5 cu.ft. of Gas
Movable Piston Head
Gage Showing Absolute Pressures

FIG. 232.—First change; change of volume and pressure in accordance with Boyle's law.

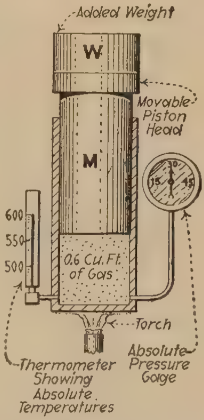


FIG. 233.—Second change; change of volume and temperature in accordance with Gay Lussac's law.

SOLUTION.—Call the volume of the gas after the first change (Fig. 232) V_2'. Then, in accordance with Boyle's law, the final volume due to the pressure change alone, as given by For. (110) = $V_2' = P_1V_1/P_2 = 1 \times 15 \div 30 = 0.5$ *cu. ft.* Then according to Gay Lussac's law, the volume due to the temperature change alone, as given by For. (131) = $V_2 = V_2'T_2/T_1 = 0.5 \times 600 \div 500 =$ 0.6 *cu. ft.*

245. The Formula Which Combines Boyle's, Charles', And Gay Lussac's Laws and which applies for a given weight of any gas, the derivation of which is given below, is this:

$$\frac{P_1V_1}{T_1} = \frac{P_2V_2}{T_2} \qquad (133) \quad \text{(units as noted)}$$

Or, by transposing,

(134) $$P_2 = \frac{P_1V_1\mathrm{T}_2}{V_2\mathrm{T}_1}$$ (final abs. pressure)

(135) $$V_2 = \frac{P_1V_1\mathrm{T}_2}{P_2\mathrm{T}_1}$$ (final volume)

(136) $$\mathrm{T}_2 = \frac{P_2V_2\mathrm{T}_1}{P_1V_1}$$ (final temperature)

Wherein: P_1 and P_2 = respectively, the initial and final absolute pressures of the gas in any pressure unit but both must be in the same unit. V_1 and V_2 = respectively, the initial and final volumes of the gas in any volume unit but both must be in the same unit. T_1 and T_2 = respectively, the initial and final absolute temperatures of the gas both on the same scale.

DERIVATION.—Repeating the three fundamental gas-law formulas and stating them in their general forms without employing any specific units: Boyle's law, For. (108) is:

(137) $$\frac{P_1}{P_2} = \frac{V_2}{V_1} \text{ or } P_1V_1 = P_2V_2$$

Charles' law, For. (120) is:

(138) $$\frac{P_1}{P_2} = \frac{\mathrm{T}_1}{\mathrm{T}_2} \text{ or } P_1\mathrm{T}_2 = P_2\mathrm{T}_1$$

Gay Lussac's law, For. (130) is:

(139) $$\frac{V_1}{V_2} = \frac{\mathrm{T}_1}{\mathrm{T}_2} \text{ or } V_1\mathrm{T}_2 = V_2\mathrm{T}_1$$

Now multiplying together the second forms of each of the above equations, there results:

(140) $$P_1V_1 \times P_1\mathrm{T}_2 \times V_1\mathrm{T}_2 = P_2V_2 \times P_2\mathrm{T}_1 \times V_2\mathrm{T}_1$$

Or performing the multiplication indicated above:

(141) $$P_1^2V_1^2\mathrm{T}_2^2 = P_2^2V_2^2\mathrm{T}_1^2$$

Extracting the square root of both sides of the equation:

(142) $$P_1V_1\mathrm{T}_2 = P_2V_2\mathrm{T}_1$$

Or transposing to a more convenient form:

(143) $$\frac{P_1V_1}{\mathrm{T}_1} = \frac{P_2V_2}{\mathrm{T}_2}$$

which is the same as For. (133).

EXAMPLE.—Solve, using For. (133) transposed, the example which is given under Sec. 244. SOLUTION.—By For. (135), $V_2 = P_1V_1\mathrm{T}_2/P_2\mathrm{T}_1 = 15 \times 1 \times 600 \div 500 \times 30 = 0.6$ *cu. ft.*

EXAMPLE.—A certain quantity of air (Fig. 234) has a volume of 40 cu ft. when at a pressure of 30 lb. per sq. in. abs. and a temperature of

80° F. The air is permitted to expand until its volume is 80 cu. ft. and simultaneously its temperature is reduced (by cooling) to 50° F. What is the absolute pressure which is exerted by the air at the end of its expansion? Solution.—80° *F.* = 80 + 460 = 540° *F. abs.* 50° *F.* = 50 + 460 = 510° *F. abs.* Now, by For. (134), $P_2 = P_1V_1T_2/V_2T_1 = 30 \times 40 \times 510 \div 80 \times 540$ = 14.2 *lb. per sq. in. abs.*

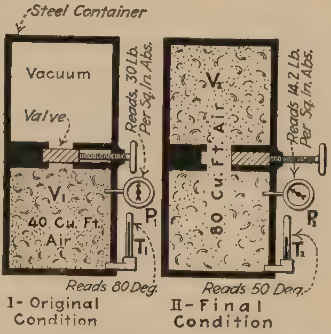


Fig. 234.—What is the final pressure, P_2, of the air?

Example.—If a city is supplied with natural gas (Fig. 235) under an agreement to pay 25 ct. per 1,000 cu. ft. when the gas is measured at atmospheric pressure (14.7 lb. per sq. in. abs.) and at 60° F., what should the city pay for 20,000 cu. ft. measured at 90° F. and 300 lb. per sq. in. gage? Solution.—Since this is a problem involving a given weight of a given gas, it may be solved by the combined gas law, Sec. 245. Applying For. (135), $V_2 = P_1V_1T_2/P_2T_1 = (300 + 14.7) \times 20{,}000 \times (460 + 60) \div [14.7 \times (460 + 90)] = 314.7 \times 20{,}000 \times 520 \div (14.7 \times 540) =$ 412,300 *cu. ft.* Hence, the city should pay $0.25 × (412,300 ÷ 1,000) = $103.08.

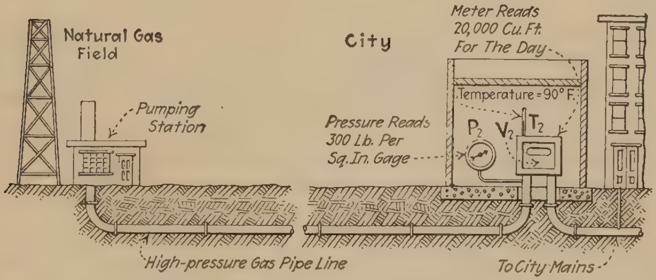

Natural Gas Field
Pumping Station
City
Meter Reads 20,000 Cu. Ft. For The Day
Temperature = 90° F.
P_2
V_2
T_2
Pressure Reads 300 Lb. Per Sq. In. Gage
High-pressure Gas Pipe Line
To City Mains

Fig. 235.—At 25 ct. per 1,000 cu. ft. measured at 14.7 lb. per sq. in. abs. and at 60° F., how much does the city owe for the day's supply of gas?

Note.—Terms Used In Those Heat-engine Problems, Which May Be Solved By Applying The General Gas Law Formulas, and which should be understood before proceeding, are: *The "bore" of an engine* is the internal diameter of its cylinder—the outside diameter of its piston. *The "stroke" of an engine* is the lineal distance, along the cylinder, which is swept through by the piston; it is equal to the travel of the crosshead. *The "clearance" or "clearance volume" of an engine* is the volume of space, in the engine cylinder, left between the adjacent cylinder head and the piston when the piston is at the end of its stroke, plus the volume of the part which leads to it; clearance is usually expressed as a ratio in per cent thus: *Clearance = (clearance volume)/(volume swept through by piston). The "displacement volume" of an engine* is the volume through which the piston sweeps.

Example.—A gas engine, which has a clearance of 20 per cent., draws in a charge of gas at atmospheric pressure and at a temperature of 70° F. The charge completely fills the clearance and the displacement volumes. The charge is then, prior to ignition, compressed into the clearance. The gage pressure, which the gas then exerts, as shown by a pressure gage, is 145.3 lb. per sq. in.; what is the temperature of the gas?

Solution.—T_2 = the unknown. $T_1 = 70 + 460 = 530°$ *F. abs.* $P_1 =$ 14.7 *lb. per sq. in. abs.* $P_2 = 145.3 + 14.7 = 160.0$ *lb. per sq. in. abs.* $V_1 =$ *(displacement volume)* + *(clearance volume)* = 100 *per cent.* + 20 *per cent.* = 120 *per cent.* V_2 = *clearance volume* = 20 *per cent.* Now, substitute in For. (136): $T_2 = P_2V_2T_1/P_1V_1 = (530 \times 160 \times 20) \div (14.7 \times 120) = 1{,}696{,}000 \div 1{,}764 = 961°$ *F. abs.* or $961 - 460 = 501°$ *F.*

Example.—Assume that the charge of gas, after being compressed, as in the preceding example, is ignited. If the temperature—combustion temperature—then becomes 3,258° F. and the piston has not moved from the final position which was specified in the example just preceding, what then will be the pressure against the piston?

Solution.—Since the gas charge here considered is the same one that was used in the first gas-engine example, the same original, initial condition may be taken for the preceding example and for this example. Hence: $P_1 = 14.7$ *lb. per sq. in. abs.* P_2 = the unknown. $V_1 = 120$ *per cent.* $V_2 = 20$ *per cent.* $T_1 = 530°$ *F. abs.* $T_2 = 3{,}258 + 460 =$ 3,718° F. *abs.* Now, substitute in For. (134): $P_2 = P_1V_1T_2/V_2T_1 = (14.7 \times 120 \times 3{,}718) \div (20 \times 530) = 6{,}558{,}552 \div 10{,}600 = 618.7$ *lb. per sq. in. abs.* Another Solution Of This Same Example could be effected by using in this example the final-condition values from the preceding example, thus: $P_2 = P_1V_1T_2/V_2T_1 = (160 \times V \times 3{,}718) \div (V \times 961) = 594{,}880 \div 961 = 618.7$ *lb. per sq. in. abs.* or $618.7 - 14.7 =$ 604 *lb. per sq. in. gage.*

Example.—The same charge of gas, which was considered in the two examples just preceding, was ignited and exploded in the previous example. It now expands and pushes the gas-engine piston before it to the end of the expansion stroke. If the pressure exerted by the gas at the end of its expansion stroke is 40 lb. per sq. in. abs., what is its temperature?

Solution.—Since the gas charge which is considered here is the same one that was used in the first gas-engine example, the same original, initial conditions which were employed in the two examples just preceding may be used in this example. Hence: T_2 = the unknown. $T_1 = 530°$ *F. abs.*, from the preceding example. $P_1 = 14.7$ *lb. per sq. in. abs.* $P_2 =$ 40 *lb. per sq. in. abs.* V remains constant, since for both the second and the first conditions it is 120 per cent. Now substitute in For. (136): $T_2 = P_2V_2T_1/P_1V_1 = (530 \times 40 \times V) \div (14.7 \times V) = 21{,}200 \div 14.7 =$

1,442° *F. abs.* ANOTHER SOLUTION OF THIS SAME EXAMPLE could be effected by using in this example, the final-condition values from the preceding example, thus: $\mathrm{T}_2 = P_2V_2\mathrm{T}_1/P_1V_1 = (3{,}718 \times 40 \times 120) \div (618.7 \times 20) = 17{,}846{,}300 \div 12{,}347 = 1{,}442°$ *F. abs.*

246. For Any Given Weight Of A Perfect Gas, The Quotient, Which Is Obtained By Dividing The Product Of Its Absolute Pressure And Volume By Its Absolute Temperature, Is A Constant; that is, the quotient has the same value for any condition of the gas. This is merely a statement, in words, of the fact which is expressed mathematically by For. (133). Or, the same fact stated in still another way is:

$$\frac{PV}{\mathrm{T}} = k \qquad \text{(constant)} \tag{144}$$

Wherein: P = the absolute pressure, which is exerted on or by any weight of the gas, in any pressure unit. V = the volume, of the same weight of gas when it is exerting the pressure P, in any volume unit. T = the absolute temperature, of the same weight of gas when it is exerting the pressure P, in any temperature unit. k = a constant value, for the given weight of gas, for any pressure-volume-temperature condition, the pressure, volume, and temperature respectively being always expressed in the same unit for each different condition. That is, this k represents a constant value in the same way that the value of k (Sec. 112) in the Boyle's-law formula remains constant for any given weight of a gas.

247. Values Of "k" For 1 Lb. Of Different Gases have been determined experimentally for practically all of the known gases. In this book such values are denoted by the symbol "k_G." They are, for some of the more common gases and for certain measurement units, given in Table 251. These Table 251 values hold only for 1 lb. of gas where: (1) *The volume is measured in cubic feet.* (2) *The absolute pressure is measured in pounds per square foot.* (3) *The temperature is measured in degrees Fahrenheit absolute.* If measurement units other than those just specified in (1), (2) and (3) are employed, then the k_G values will change accordingly.

EXPLANATION.—IN DETERMINING EXPERIMENTALLY THE VALUE OF k_G FOR A GIVEN GAS, it is only necessary to measure simultaneously the: (1) *absolute pressure*, and the corresponding (2) *volume*, (3) *absolute* *temperature*, and (4) *weight* of the quantity of gas under consideration. The quantity may be any that is convenient. Similarly, the pressure and the corresponding volume and temperature condition may be any that are convenient. Then, applying For. (144), multiply together the corresponding absolute pressure, P, and volume, V, and divide their product by the absolute temperature, **T**. The result will be k for the total quantity of gas under consideration. As stated in the preceding section, the value of k for any given weight of any certain gas will always be the same regardless of its pressure, volume and temperature condition. Then, by dividing the "k" value thus computed by the number of pounds in the total quantity of gas, the value of k for 1 lb., that is, the value of k_G is obtained. To explain the reason for this, suppose that 1 lb. of a gas, at a given temperature and pressure, occupies 1 cu. ft. It is obvious that, at the same pressure and temperature, 2 lb. of the gas must occupy 2 cu. ft., and **W** pounds must occupy **W** cu. ft. Now, since $k = PV/\mathbf{T}$ and since V varies directly as the weight of gas under consideration, it follows that k must also vary directly with the weight.

Note.—It Is Also True That, For Any Gas: k_G = [(*Its specific heat at constant pressure*) − (*Its specific heat at constant volume*)] × 778. This is here stated merely as an interesting fact; no endeavor will be made herein to explain the reason therefor.

Example.—It is found by experiment that 1 cu. ft. of air at atmospheric pressure and at a temperature of 32° F., weighs 0.080,71 lb. What is the gas constant, k_G, for air. Solution.—By definition, *atmospheric pressure* = 14.7 *lb. per sq. in. abs.* = 14.7 × 144 = 2116.8 *lb. per sq. ft. abs.* Also, taking the more accurate value of "459.6°," instead of the usual "460°" for the difference between the absolute zero and the Fahrenheit zero: 32° *F.* = 32 + 459.6 = 491.6° *F. abs.* Now substitute in For. (144) to obtain *the constant for this weight* (0.080,71 *lb.*) *of air* = $k = PV/\mathbf{T}$ = 2116.8 × 1 ÷ 491.6 = 4.306. The same constant "4.306" would be obtained, for this weight of air, for any other temperature—pressure—volume condition. Now divide by the weight of air to obtain *the gas constant for* 1 *lb. of air* = k_G = 4.306 ÷ 0.080,71 = 53.34, which is the same value as that given for air in Table 251.

248. The General Gas Law (The Perfect-gas Law) states the relation which exists between the pressure, volume, absolute temperature, and weight of a perfect gas. It is generally expressed as an equation as shown by For. (145). It is a very important law and one with which every engineer should be familiar because it recognizes in one equation every property of a given gas that may change, that is, which is variable. It is based on a combination of Boyle's, Charles' and Gay Lussac's laws, as is shown in the following derivation.

249. The General-gas-law Formulas are given below. Note that, in substituting in these formulas, *pounds-per-square-foot* absolute-pressure values and degrees Fahrenheit absolute-temperature values must be used. But these may readily be derived from gage-pressure and degree-Fahrenheit values, as explained in Secs. 17 and 62.

(145) $$PV = \mathbf{W}k_G\mathbf{T}$$ (pressure and volume)

hence, transposing:

(146) $$P = \frac{\mathbf{W}k_G\mathbf{T}}{V}$$ (lb. per sq. ft. abs.)

furthermore:

(147) $$V = \frac{\mathbf{W}k_G\mathbf{T}}{P}$$ (cu. ft.)

and:

(148) $$\mathbf{T} = \frac{PV}{\mathbf{W}k_G}$$ (deg. Fahr. abs.)

and:

(149) $$\mathbf{W} = \frac{PV}{k_G\mathbf{T}}$$ (lb.)

and:

(150) $$k_G = \frac{PV}{\mathbf{WT}}$$ (gas constant)

and:

(151) $$D = \frac{\mathbf{W}}{V} = \frac{P}{k_G\mathbf{T}}$$ (lb. per cu. ft.)

Wherein: P = the absolute pressure of the gas, in pounds per square foot. V = the volume of the gas, in cubic feet. $\mathbf{W}$ = the weight of the gas, in pounds. k_G = a constant which varies with the kind of gas and with the units of measurement which are used; for the units here specified, values for different gases are given in Table 251. $\mathbf{T}$ = the absolute temperature of the gas in Fahrenheit degrees. D = the density of the gas, in pounds per cubic foot.

DERIVATION.—For. (144) is merely another way of expressing For. (133) which is derived, as there shown, by combining Boyle's, Charles' and Gay Lussac's laws. Now, For. (144) is for "any given weight of gas." That is, it assumes that the weight of gas under consideration is constant. Thus, repeating For. (133) but using symbols which express: (1) *Pressure in pounds per square foot*, (2) *volume in cubic feet*, (3) *temperature in degrees Fahrenheit absolute*, there results:

(152) $$k = \frac{PV}{\mathrm{T}} \qquad \text{(constant for any given weight of gas)}$$

Now, by definition, k_G = *gas constant for 1 lb. of gas.* It was shown under Sec. 247 that if k_G, which is the gas constant for 1 lb. of the gas which is under consideration, be multiplied by **W**, which represents the total weight in pounds of the gas, the result will be k, the constant for the total amount of gas. That is:

(153) $$k = \mathrm{W}k_G \qquad \text{(constant for any given weight of gas)}$$

Now, substituting the equivalent of k from For. (153) in For. (152) there results:

(154) $$\mathrm{W}k_G = \frac{PV}{\mathrm{T}}$$

and then transposing:

(155) $$\mathrm{W}k_G\mathrm{T} = PV$$

which is the same as For. (145).

250. The General-gas-law Formulas Are The Engineer's Practical Working Formulas.—Any problem which can be solved by applying either Boyles', Charles', or Gay Lussac's laws can be solved with them. Furthermore, by their use many problems, to which none of these three laws apply, can be worked. Hence, they are the only formulas that need be memorized for any of these computations. The examples which are given below illustrate only a few of their many applications.

NOTE.—THE GENERAL GAS LAW HOLDS ONLY FOR PERFECT GASES—as they are defined in Sec. 226 as do all of the other laws treated in this division. In fact, the following definition is sometimes given: *A gas which has properties such that it conforms exactly to the general gas law is a perfect gas.* But the performances of many ordinary gases conform sufficiently to the general gas law that, for the usual engineering computations, it provides results well within the limits of required accuracy.

251. Specific Heats, Values Of "k" And Values Of "k_G" For Some Of The More Common Gases.—Specific-heat values shown are average values over the temperature ranges (32°–400° F.) ordinarily encountered in practice. Values in line 9 are variable. All others are from Marks' "Mechanical Engineers' Handbook." See Sec. 247 for units which must be employed when the k_G values are used. The substances of items 1, 2 and 10 are not to be treated as gases unless highly superheated; see Div. 11.

	Name of gas	Chemical symbol	Specific heat		$k = C_P \div C_V$	k_G = Gas constant $= (C_P - C_V) \times 778$
			At constant pressure, C_P	At constant volume, C_V		
1	Sulphur dioxide......	SO_2	0.154	0.123	1.25	24.10
2	Carbon dioxide.......	CO_2	0.210	0.160	1.31	35.09
3	Oxygen.............	O_2	0.217	0.155	1.40	48.25
4	Air.................	......	0.241	0.171	1.40	53.34
5	Nitrogen...........	N_2	0.247	0.176	1.40	54.99
6	Ethylene...........	C_2H_4	0.400	0.330	1.20	55.08
7	Carbon monoxide....	CO	0.243	0.172	1.41	55.14
8	Acetylene..........	C_2H_2	0.350	0.270	1.28	59.34
9	Blast furnace........	......	0.245	0.174	1.40	55.05
10	Ammonia...........	NH_3	0.523	0.399	1.31	90.50
11	Methane............	CH_4	0.593	0.450	1.32	96.31
12	Hydrogen..........	H_2	3.42	2.44	1.40	765.9

252. The Problems Which Can Be Solved With The General Gas Law, Fors. (145) to (151), are: (1) *Those in which values for four of the five properties—pressure, volume, temperature, weight, and kind of gas— of a quantity of gas are known for a certain condition and it is desired to determine the value of the fifth property for that condition.* (2) *Those in which values for four of the five properties of a quantity of gas are known for a first given condition and, for a second condition, two of the values change while the other three remain constant; then, knowing the final value of one of the changed properties, the value of the other changed property may be computed.*

EXAMPLE.—A vessel (Fig. 236) contains 5 lb. of air. The gage pressure is 20 lb. per sq. in. The temperature is 90° F. What is the cubical content of the vessel? SOLUTION.—The *absolute pressure* = (20 + 14.7) × 144 = 5,000 *lb. per sq. ft.* The *absolute temperature* = 460 + 90 = 550° *F. abs.* From Table 251, *k_G for air* = 53.34. Now substituting the known values in For. (147): $V = Wk_GT/P = (5 \times 53.34 \times 550) \div 5{,}000 = 29.3$ *cu. ft.*

Example.—A receiver (Fig. 237) contains 800 cu. ft. of compressed air at a gage pressure of 120 lb. per sq. in. Its temperature is 80° F. What is the weight of the air. Solution.—The *absolute pressure* = $(120 + 14.7) \times 144 = 19{,}400$ *lb. per sq. ft.* The *absolute temperature* = $460 + 80 = 540°$ *F. abs.* From Table 251, k_G *for air* = 53.34. Now substitute in For. (149): $W = PV/k_GT = (19{,}400 \times 800) \div (53.34 \times 540) = 539$ *lb.*

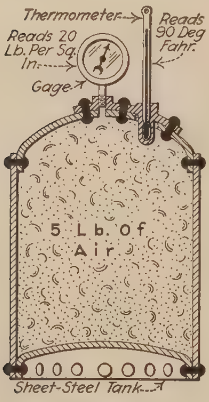


Fig. 236.—What is the volume of the vessel?

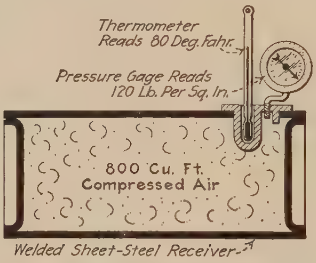

Thermometer Reads 80 Deg. Fahr.
Pressure Gage Reads 120 Lb. Per Sq. In.
800 Cu. Ft. Compressed Air
Welded Sheet-Steel Receiver

Fig. 237.—What is the weight of the air?

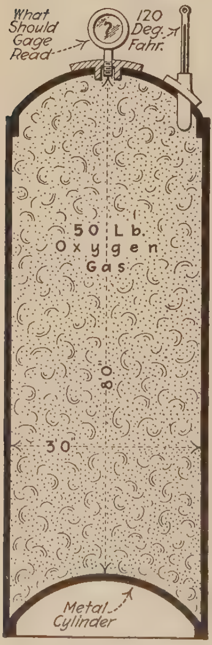


Fig. 238.—What is the gage pressure?

Example.—It is desired to store 50 lb. of oxygen gas in a metal cylinder (Fig. 238) which is 3 ft. in diameter and 8 ft. long. What must be the pressure shown by the gage on the tank when it contains 50 lb. of oxygen, if the oxygen is pumped in at a temperature of 120° F.? Solution.—The *volume of the tank* = $0.785 \times 3 \times 3 \times 8 = 56.5$ *cu. ft.* From Table 251, for oxygen, $k_G = 48.25$. The *absolute temperature* = $120 + 460 = 580°$ *F. abs.* Now substitute in For. (146): $P = Wk_GT/V = (50 \times 48.25 \times 580) \div 56.5 = 24{,}765$ *lb. per sq. ft. abs.* *Pounds per square inch absolute* = $24{,}765 \div 144 = 171.9$ *lb. per sq. in. abs.* *Gage pressure* = *absolute pressure* $- 14.7 = 171.9 - 14.7 = 157.2$ *lb. per sq. in. = pressure which should be shown by gage on cylinder.*

Example.—An air compressor pumps 120 cu. ft. per min. of free air (atmospheric pressure), which is at an average temperature of 70° F. Disregarding the effect of moisture in the air, what is the weight of the air which is pumped each minute? Solution.—From Table 251, for air, $k_G = 53.34$. Now, substitute in For. (149): $W = PV/k_GT = [(14.7 \times 144) \times 120] \div [53.34 \times (70 + 460)] = [2{,}116.8 \times 120] \div [53.34 \times 530] = 254{,}016 \div 28{,}276 = 9.0$ *lb.*

EXAMPLE IN WHICH THE VALUES FOR FOUR PROPERTIES ARE KNOWN FOR A FIRST GIVEN CONDITION AND, FOR A SECOND CONDITION, TWO OF THE VALUES CHANGE WHILE THE OTHER THREE REMAIN CONSTANT, it being necessary to determine the final value of one of the changed properties: A steel container holds 800 cu. ft. of air which is at a pressure of 19,400 lb. per sq. ft. abs. and a temperature of 540° F. abs. What will be the pressure exerted by the air if its temperature is increased to 600° F. abs.? SOLUTION.—From Table 251, for air, $k_G = 53.34$. Hence, by For. (149), $\mathrm{W} = PV/k_G\mathrm{T} = 19{,}400 \times 800 \div (53.34 \times 540) = 538.7$ *lb.* Now substitute in For. (146): $P = \mathrm{W}k_G\mathrm{T}/V = 538.7 \times 53.34 \times 600 \div 800 = 21{,}567$ *lb. per sq. ft. abs.*

253. The "Density" Of Any Substance is its mass per unit of volume. In engineering, density is usually considered as the weight of a unit volume of a substance—that is, if a body's weight be divided by its volume, the result is called its density. The weight and volume may be measured in any convenient units. If the weight be measured in pounds and the volume in cubic feet, the resultant density is expressed in *pounds per cubic foot.* This unit (lb. per cu. ft.) is very widely used in engineering work. The formula for density, expressed in this unit, is:

$$D = \frac{\mathrm{W}}{V} \qquad \text{(lb. per cu. ft.)} \tag{156}$$

which, by transposition, gives:

$$V = \frac{\mathrm{W}}{D} \qquad \text{(cu. ft.)} \tag{157}$$

and

$$\mathrm{W} = VD \qquad \text{(pounds)} \tag{158}$$

Wherein: D = the density of a substance, in pounds per cubic foot. W = its weight, in pounds. V = its volume, in cubic feet.

EXAMPLE.—If 6 cu. ft. of water weigh 375 lb., what is the density of the water? SOLUTION.—By For. (156), $D = \mathrm{W}/V = 375 \div 6 = 62.5$ *lb. per cu. ft.*

EXAMPLE.—If the density of air (under certain conditions) is 0.1 lb. per cu. ft., what volume will 8 lb. of air occupy? SOLUTION.—By For. (157), $V = \mathrm{W}/D = 8 \div 0.1 = 80$ *cu. ft.*

EXAMPLE.—What weight of hydrogen will be contained in a 5-cu. ft. container if the density of the hydrogen is 0.03 lb. per cu. ft.? SOLUTION.—By For. (158), $\mathrm{W} = VD = 5 \times 0.03 = 0.15$ *lb.*

254. The Density Of Any Substance Will Vary with its temperature or with any other property which affects its volume. Thus, since heating a solid expands it but does not (ordinarily) change its weight, it is obvious that heating will decrease the density of a solid. With gases, the density depends on the pressure, temperature, and kind of gas. With a given weight of a certain gas, the density varies with the pressure and temperature. Formulas for the density of a gas and for its variations with pressure and temperature are derived by substituting from For. (156) into the gas-law formulas which have already been developed. Thus, for a given weight of any gas at constant temperature (Boyle's law):

(159) $$\frac{P_1}{P_2} = \frac{D_1}{D_2}$$ (ratio)

or

(159*A*) $$D_2 = \frac{D_1 P_2}{P_1}$$ (final density)

at constant volume, (Charles' law):

(160) $$D_1 = D_2$$ (density)

at constant pressure (Gay-Lussac's law):

(161) $$\frac{\mathbf{T}_1}{\mathbf{T}_2} = \frac{D_2}{D_1}$$ (ratio)

or

(162) $$D_2 = \frac{D_1 \mathbf{T}_1}{\mathbf{T}_2}$$ (final density)

For a given weight of any gas (combined law):

(163) $$\frac{P_1}{D_1 \mathbf{T}_1} = \frac{P_2}{D_2 \mathbf{T}_2}$$ (ratio)

or

(164) $$D_2 = \frac{D_1 \mathbf{T}_1 P_2}{\mathbf{T}_2 P_1}$$ (final density)

Now from For. (156) $D_F = \mathbf{W}/V$. Then, substituting this D_F for its equivalent in For. (151) for the general gas law, it follows that for any gas.

$$D_F = \frac{P_F}{k_G \mathrm{T}_F} \qquad \text{(lb. per cu. ft.)} \tag{165}$$

Wherein: D = density. P = absolute pressure. $\mathbf{T}$ = absolute temperature. The units may be any convenient ones; the subscripts $_1$ and $_2$ referring respectively to the initial and final conditions of a gas which undergoes a change of condition. D_F = density, in pounds per cubic foot. P_F = absolute pressure, in pounds per square foot. T_F = absolute temperature, in degrees Fahrenheit. k_G = gas constant, as given in Table 251.

EXAMPLE.—The density of a certain gas is 0.2 lb. per cu. ft. when under 200 lb. per sq. in. abs. pressure. What will be the density of the same gas under 30 lb. per sq. in. abs. and at the same temperature? SOLUTION.—By For. (159A), $D_2 = D_1P_2/P_1 = 0.2 \times 30 \div 200 = 0.03$ *lb. per cu. ft.*

EXAMPLE.—If the density of air is 0.15 lb. per cu. ft. when under a certain pressure and at 40° F., what will be its density when under the same pressure but at 1,140° F.? SOLUTION.—By For. (162), $D_2 = D_1\mathrm{T}_1/\mathrm{T}_2 = 0.15 \times (40 + 460) \div (1{,}140 + 460) = 0.15 \times 500 \div 1{,}600 = 0.047$ *lb. per cu. ft.*

EXAMPLE.—A given weight of gas, when under 30-in. mercury column and at 60° F. has a density of 0.06 lb. per cu. ft. What will be its density when under 10 in. mercury column and at 20° F.? SOLUTION.—By For. (164), $D_2 = D_1\mathrm{T}_1P_2/\mathrm{T}_2P_1 = 0.06 \times (60 + 460) \times 10 \div [(20 + 460) \times 30] = 0.06 \times 520 \times 10 \div (480 \times 30) = 0.021{,}7$ *lb. per cu. ft.*

EXAMPLE.—What is the density of oxygen at atmospheric pressure and 32° F.? SOLUTION.—From Table 251, k_G (for oxygen) = 48.25. Hence by For. (165): $D_F = P_F/k_G\mathrm{T}_F = (14.7 \times 144) \div (48.25 \times 492) = 0.089{,}2$ *lb. per cu. ft.*

255. Table Of Absolute And Relative Densities Of Various Gases. (Based on values in Marks' "Mechanical Engineers' Handbook," p. 316). Carbon dioxide and ammonia, at the pressure and temperature given, are sufficiently superheated that they may reasonably be considered as gases.

Kind of gas	Absolute density in lb. per cu. ft., at atmospheric pressure, or 14.7 lb. per sq. in. absolute		Relative density as compared to air
	64° F.	32° F.	
Air	0.0761	0.0807	1.000
Oxygen	0.0840	0.0892	1.105
Nitrogen	0.0737	0.0783	0.970
Hydrogen	0.00529	0.00562	0.0696
Carbon monoxide	0.0734	0.078	0.968
Carbon dioxide	0.1156	0.1227	1.520
Ammonia	0.04483	0.0476	0.590
Acetylene	0.0684	0.0725	0.899
Methane	0.0421	0.0447	0.554
Ethylene	0.0738	0.0780	0 969

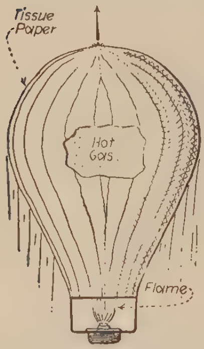


FIG. 239.—Hot gas lifts the toy balloon.

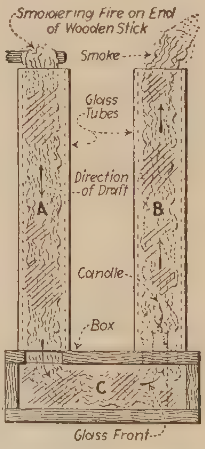


FIG. 240.—Air-draft produced by heat.

256. Air Drafts Are Caused By Differences In The Density Of The Air.—When a body of air is heated it expands; its density decreases. It thus becomes lighter per unit of volume. Therefore, it tends to ascend, due to its displacement by the cooler and heavier air from above. Thus the less dense air is forced upward by the denser air above it just as a cork is forced upward in water by the denser water above it. Toy balloons (Fig. 239), also many balloons which are built for actual service, derive their buoyancy from the low-density hot air and combustion gases with which they are inflated. The draft (see the author's STEAM BOILERS) which is produced by all chimneys, power-plant and others, likewise depends upon this principle.

EXAMPLE.—Two glass chimney-tubes, *A* and *B* (Fig. 240) are placed over apertures in a box, *C*, which has a glass side. A lighted candle is placed in the tube *B*. Thereby the air in tube *B* becomes heated and its density decreases. Therefore it rises, due to its displacement by the cooler denser air which decends through tube *A*. A draft is thus produced which forces the smoke downward from the smoldering fire at the top of *A*. The smoke can then be seen flowing down through chimney *A* into the box, *C*, and thence upward through chimney *B*. See also Fig. 241.

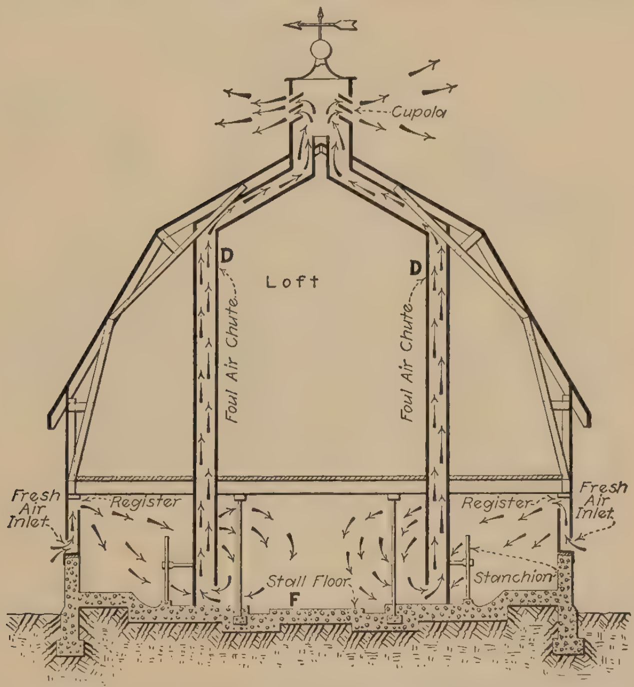


FIG. 241.—Barn ventilated by rising warm-air currents. (The air in the stall floor, *F*, becomes warmer than the outside air due to the heat given off by the animals. It is then displaced by colder outside air and forced up through ducts, *D*.)

EXAMPLE.—Each of the chimney-tubes, *A* and *B* (Fig. 240) is assumed to be 100 ft. high and of 1 sq. ft. cross-section. The temperature in tube *A* is 64° F., and in tube *B* 464° F. What pressure, in inches water column, tends to force the smoke up through tube *B*? SOLUTION.—By

Table 255 the *density of the air in tube A under atmospheric pressure at* 64° *F.* = 0.076,1 *lb. per cu. ft.*, the *absolute temperature in tube A* = 460 + 64 = 524° *F. abs.*, and in tube B = 460 + 464 = 924° F. abs. By For. (162) the *density of the air in tube B* = $D_2 = D_1\mathrm{T}_1/\mathrm{T}_2 = (0.076{,}1 \times 524) \div 924 = 0.043{,}2$ *lb. per cu. ft.* The *volume of air in each tube* = 100 × 1 = 100 *cu. ft.* Hence, the *weight of the air in tube A* = 100 × 0.076,1 = 7.61 lb., while the *weight of the air in tube B* = 100 × 0.043,2 = 4.32 *lb.* Therefore, the *boosting pressure in tube B* = 7.61 − 4.32 = 3.29 *lb. per sq. ft.* = 3.29 ÷ 144 = 0.022,8 *lb. per sq. in.* By For. (9) the *equivalent height of water column* = $P_I = 27.684P = 27.684 \times 0.022{,}8 = 0.634$ *in. water column.*

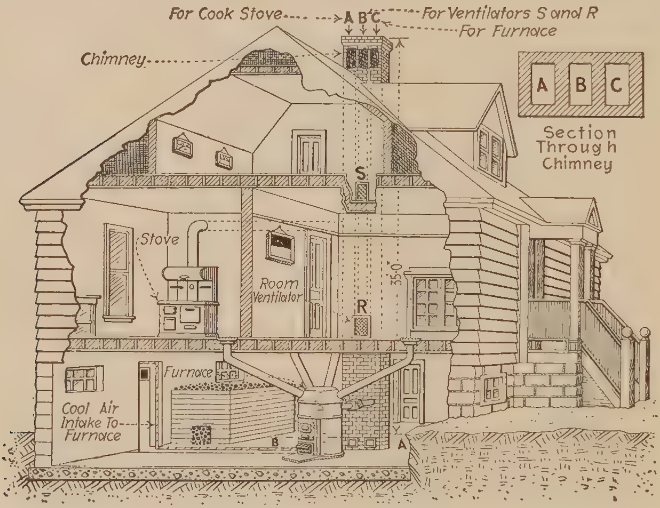


Fig. 242.—Illustrating chimney draft (the three-flue chimney provides draft for the furnace and cook-stove and also, by means of ventilators, S and R, ventilates the rooms).

Example.—The chimney of a dwelling (Fig. 242) extends 35 ft. above the furnace in the basement. The temperature of the outside air is 32° F. The average temperature of the gases inside the chimney is 450° F. What is the draft pressure produced thereby, in inches of water-column? Solution.—By Table 255 *the density of air at* 32° = 0.080,7 *lb. per cu. ft.* By For. (162), the approximate *density of the combustion gases in the chimney* = $D_2 = D_1\mathrm{T}_1/\mathrm{T}_2 = 0.0807 \times (460 + 32) \div (460 + 450) = 0.043{,}6$ *lb. per cu. ft.* The *pressure of the column of chimney gases* (on line AB, coinciding with furnace grate) = 35 × 0.043,6 = 1.53 *lb. per sq. ft.* The *pressure, of an equivalent column of the external air* = 35 × 0.080,7 = 2.87 *lb. per sq. ft. of base area.* Hence, the *draft-pressure* = 2.82 − 1.53 = 1.29 *lb. per sq. ft.* = 1.29 ÷ 144 = 0.008,96 *lb. per sq. in.* By For. (9), the *equivalent height of water column* = $P_I = 27.684P = 27.684 \times 0.008{,}96 = 0.248$ *in. water column.*

257. The Heat Effects In Gases Are Different From Those In Solids And Liquids.—As explained in Secs. 96 and 102, (Div. 4), the addition of heat to a *solid* body always produces an increase in its temperature (the heat does vibration work, Sec. 97, and does only an inappreciable amount of external work (Sec. 99). If the solid is at its melting temperature, then the addition of heat does disgregation work (Sec. 98) and an almost inappreciable amount of external work. Likewise, the addition of heat to a *liquid* always increases its temperature (does vibration work) and does only an inappreciable amount of external work; if the liquid is at its boiling temperature, then the addition of heat does disgregation work and an appreciable amount of external work. But, the addition of heat to *gas* at any temperature may or may not increase its temperature, may or may not do external work, and, as will be shown, never does any disgregation work. Whether or not vibration or external work is done, depends on the rates at which the gas is heated and at which it is permitted to do external work. The gas temperature may even increase without the addition of any heat from without. These phenomena will be explained in following sections.

258. No Disgregation Work Is Done When A Perfect Gas Is Heated Or Cooled.—The truth of this statement was first shown by Joule with the apparatus shown in Fig. 243. Later experiments by Lord Kelvin (Sir William Thompson) revealed that Joule's results were slightly in error. The experiment is now frequently referred to as the "Joule-Thompson effect."

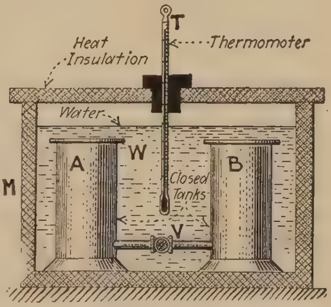


Fig. 243.—The apparatus which was used by Joule to prove that no disgregation work is done when a gas expands.

Explanation.—Joule placed two equal-sized containers (*A* and *B*, Fig. 243) in a tank of water, *W*, and provided a very sensitive thermometer, *T*, for measuring the temperature of the water. The tank, *W*, was well insulated to prevent heat flow into or out of *W*. He compressed air into *A* until the pressure was 22 atmospheres and exhausted all of the air from *B*. After the whole apparatus had reached the temperatures of the room, he opened the valve, *V*, in the pipe which connected *A* and *B* and watched *T* to observe how the temperature would vary. He could observe no variation.

Now, as explained in Sec. 96, the three ways in which heat may be expended are as vibration work, disgregation work, and external work. This thought is expressed by For. (50) which is repeated here:

$$Q = Q_V + Q_D + Q_E \qquad \text{(B.t.u.)} \tag{166}$$

Wherein: Q = heat added to the substance. Q_V = heat expended in doing vibration work. Q_D = heat expended in doing disgregation work. Q_E = heat expended in doing external work. All quantities being expressed in British thermal units.

Now, in Joule's experiment: (1) No heat was added to or abstracted from the air because the whole apparatus was insulated and was at room temperature. Hence $Q = 0$. (2) No change in temperature was noted. Hence, no vibration work was done, and $Q_V = 0$. (3) No external work was done by the air because there was no means of conveying it to or from the apparatus. Hence, $Q_E = 0$. Therefore, by substituting the values obtained in Joule's experiment into For. (166), after transposing there results: $Q_D = Q - Q_V - Q_E = 0 - 0 - 0 = 0$. Hence, it was concluded that for air $Q_D = 0$.

The later experiments by Lord Kelvin showed that, although the temperature remains *nearly constant* in the above-described experiment, there is a slight variation. The variation is very slight for the "permanent" gases (Sec. 348) at ordinary temperatures and it is assumed that for a perfect gas (Sec. 226) there would be no variation. The variation for actual gases grows larger, the lower the temperature at which the experiment is performed. The reason for this is that the gases become more and more like vapors, Div. 11, as their liquefaction temperatures are approached.

259. Heat Transferred To (Or From) A Perfect Gas May Produce (Is Produced By) Either Or Both Of Two Effects—Vibration Work And External Work.—Since it is possible to increase the temperature of a gas by heating it, it is obvious that heat energy, when added to a gas, can do vibration work. Furthermore, since heating a gas often causes it to expand or increase in volume, it is also obvious that the added heat energy can cause the gas to move substances (moving *M* and *W* in Fig. 233 for example) which restrict its volume. That is, the added heat energy can cause the gas to do external work. In any case, the amounts of vibration work and external work that are produced depend on the rate at which expansion is permitted to proceed.

EXAMPLE.—Suppose, Fig. 244, that a certain weight of gas is confined in a cylinder which is fitted with a handled piston, thermometer, and pressure gage. At 70° F., and 30 lb. per sq. in. abs. the gas is found to occupy 1 cu. ft. (condition *a*, Fig. 244). The piston is now held in the position shown while heat is applied to the cylinder until the thermometer reads 600° F. The gage will now show a pressure of 60 lb. per sq. in. abs. (by Charles' law, Sec. 237). But, since the gas did not force out the piston, it did no external work. Hence, the heat added in passing from condition *a* to condition *b* was all used in raising the temperature of the gas—in doing vibration work.

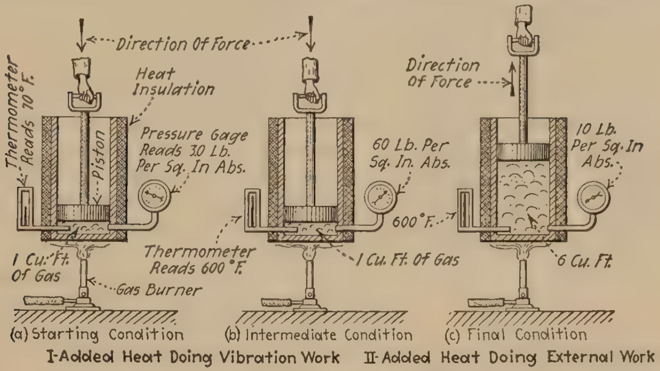


FIG. 244.—Illustrating how the heat energy which is added to a gas may do either vibration work or external work.

When condition *b* is reached, the heating is continued but, instead of holding the piston in one position, the operator now, partially restraining it, permits the piston to rise at such a rate that the thermometer continually shows 600° F. After an interval, the volume of the gas will have increased to 6 cu. ft. and the pressure will have decreased to 10 lb. per sq. in. abs. (condition *c*, Fig. 244). In passing from condition *b* to condition *c*, the gas has done external work in forcing out the piston against the resistance of the operator's hand but, since the temperature remained constant, no vibration work was done. Hence, in *II*, the heat energy was all used in doing external work.

260. A Gas Generally Does External Work When It Expands.—All gases exert pressure. If a gas is confined in a closed vessel, it exerts pressure on the walls of the vessel because the gas molecules, in their vibratory motion, strike the walls of the vessel (Sec. 50). Therefore, the walls of the vessel provide a resistance to the pressure of the gas. If the gas is permitted to expand, then the walls of the vessel or a part of them must have been moved. This motion of the walls of the vessel constitutes an instance of motion against resistance (which is work, Sec. 20). But the pressure of the gas has aided in (or been the entire cause of) the motion of the walls of the vessel. Hence, the gas has, by reason of its pressure, done external work.

Explanation.—Assume that a certain weight of gas is confined between the end of a cylinder *A*, Fig. 245, and a piston, *M*, which has been inserted through the open end of the cylinder. The gas exerts a certain pressure against the face of the piston. This pressure tends to force the piston out of the cylinder (in the direction of the arrow). If the piston is permitted to move to the position *N*, the gas must have aided in the piston's motion. Therefore, the gas has done external work.

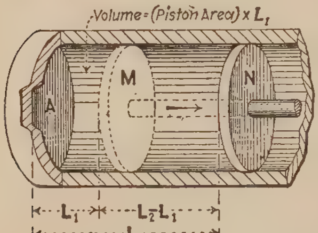


Fig. 245.—Showing that an expanding gas does external work.

Note.—A Throttling Or Frictional Expansion is one during which no external work is done by the expanding fluid. This occurs when a gaseous substance flows through a small opening from a region of high pressure to one of lower pressure, gaining velocity as it flows, which velocity is then destroyed. The substance is said to do work on itself as it increases its velocity—the work being stored in the substance in the form of kinetic energy. But, when the kinetic energy disappears as the velocity again decreases, the kinetic energy is reconverted into heat energy. Instances of throttling expansion are: (1) Joule's experiment, Sec. 258. (2) The pressure drop which accompanies the flow of a gaseous fluid through a pipe or restricted opening. Throttling expansions will not be further discussed in this division. See Sec. 387 for the throttling expansion of vapors.

261. Work May Be Represented Graphically By An Area.—As defined in Sec. 21, *work* is the product of *force* times *distance*. Since the area of any figure or diagram is the product of a length times a height, it is possible to so draw a figure that its length shall represent a distance (or force) and that its height shall represent a force (or distance). Then, its area must represent work (see explanation below). It will also be shown that work may be represented by a figure whose height represents pressure and whose length represents volume.

Explanation.—Assume that a constant force of 12 lb. is required (Fig. 246) to move an object in a given direction and that the object is moved 8 ft. from a starting point by this force. A rectangle *OBCD*, Fig. 247, is drawn, 12 units in height and 8 units in length. Its area (12 × 8 = 96 *squares*) then represents 96 units of work. Since each unit of height represents 1 lb. and each unit of length represents 1 ft., each unit of area represents 1 lb. × 1 ft. or 1 ft.-lb. Hence, the area *OBCD* represents 96 ft.-lb. of work. If, now, a constant force of 9 lb. is required (Fig. 248) to move the object from the 8-ft. mark to a 15-ft. mark (measured from the same starting point as above), the force of 9 lb. will act through a distance of (15 − 8) or 7 ft. Hence, for this second movement the *work done* = 9 × 7 = 63 *ft.-lb.* as represented by the area *DEFG*, Fig. 247.

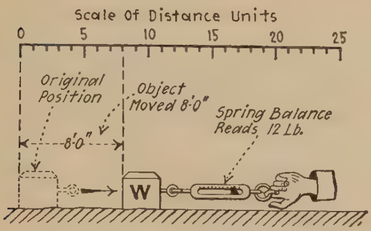


FIG. 246.—Object *W* moved 8 ft. by a constant force of 12 lb.

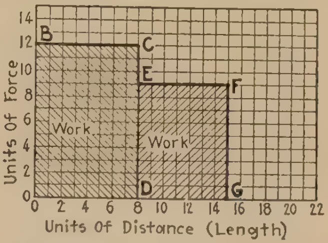


FIG. 247.—A force-distance work diagram. The shaded areas represent work.

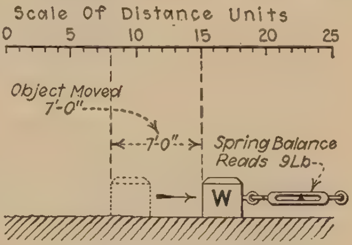


FIG. 248.—Object *W* moved 7 ft. by a constant force of 9 lb.

Assume, in a second case (Fig. 249), that a constant force of 48 lb. acts through a distance of 40 ft. A unit of height may be taken to represent a force of 4 lb. Then the 48-lb. force will be represented by 12 units (*OB*, Fig. 247). A unit of length on the diagram may be taken to represent 5 ft. Then, the 40-ft. distance will be represented, by 8 units

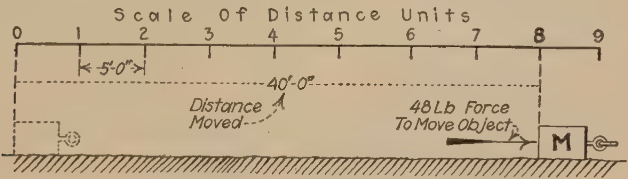


FIG. 249.—Object *M* is moved 40 ft. by a 48-lb. force.

(*OD*, Fig. 247). The work done by the force will then be represented, as in the first case by the area *OBCD* or 96 area work units. But now each area unit represents 4 *lb.* × 5 *ft.* = 20 *ft.-lb.* Hence, in this case, the area

OBCD represents 96 × 20 = 1,920 *ft.-lb.* which is the work done by the 48-lb. force acting through a distance of 40 ft.

Note.—The Area Under A Force-distance Graph Also Represents The Work Done When The Force Is Not Constant.—If, Fig. 250, in acting through the first 4 ft., a force increases uniformly from 4 to 6 lb., then *the work done* = (*average force*) × (*distance*) = [(4 + 6)/2] × 4 = 5 × 4 = 20 *ft.-lb.* which is the area of the figure *ABCD*. Then, if in acting through the next 4 ft. the force increases to 7 lb., the average force will be 6.5 lb. and the *work done* = 6.5 × 4 or 26 *ft.-lb.*, as represented by the area *DCEF*. If then the force in acting through the next 6 ft. decreases uniformly to 5 lb., the average force will be 6 lb. and the *work done* = 6 × 6 *or* 36 *ft.-lb.*, as represented by the area *FEGH*. Thus the area *ABCEGHA* represents the total work done by the varying force in acting through the total distance of 14 ft. That is, *total work done* = 20 + 26 + 36 = 82 *ft.-lb.*

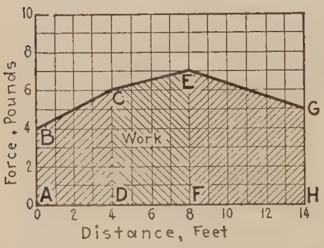


Fig. 250.—Force-distance "work" diagram for a varying force.

262. The Area Under A Pressure-volume Graph Also Represents Work, as is explained below. The pressure-volume graph can readily be drawn for an expanding (or compressed) gas. Hence, the finding of the area under such a graph affords a convenient means for finding the work done by the gas during its expansion or on the gas during its compression.

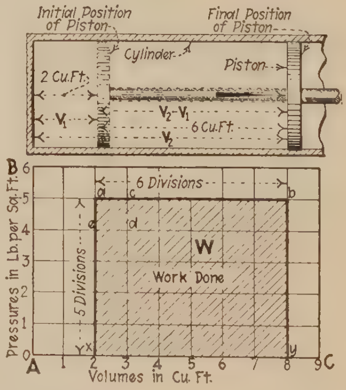


Fig. 251.—Pressure-volume work diagram showing work done by expansion. (Absolute pressure in cylinder is assumed to remain constant.) *Work done* = *Volume* × *Pressure* = (8 − 2) × 5 = 6 × 5 = 30 *ft.-lb.*

Explanation.—Assume that (Fig. 251) a cylinder is fitted with a tight-fitting piston between which and the end of the cylinder there is a volume, V_1, of 2 cu. ft. of a gas at a pressure of 5 lb. per sq. ft. abs. Assume that, by heating, the gas is caused to expand at constant pressure to a volume, V_2, of 8 cu. ft. Plot, as shown by the lower diagram in Fig. 251, pressures along the vertical scale *AB* and volumes along the horizontal scale *AC*. The line *ab* will represent the expansion of the gas. Since each unit of volume represents 1 cu. ft., each division such as *ac* which represents 1 cu. ft., must also represent a certain distance through which the piston was moved. If the area of the piston in square feet is denoted by the symbol A_P, then *ac* will denote a distance of: 1 *cu. ft.* ÷ A_P *sq. ft.* = $1/A_P$ *ft.* Also, since a pressure of 1 lb. per sq. ft. is represented by each vertical division on the graph, each division such as *ea* must also represent a certain force on the piston. This force is *pressure* × *area* = 1 × A_P *lb.* Hence, each square of the area, *W*, such as *acde*, must (see explanation under Sec. 261) represent $(1/A_P) \times (1 \times A_P)$ = 1 *ft. lb.* Therefore, the work done by the expanding gas is represented by the area *xaby* or 5 × 6 = 30 *ft.-lb.*

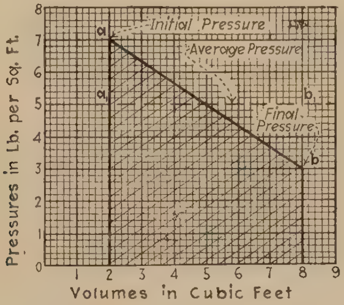


FIG. 252.—Pressure-volume work diagram with falling pressure. (*Work Done* = *Volume* × *Pressure* = (8 − 2) × 5 = 6 × 5 = 30 *ft.-lb.*

NOTE.—THE AREA UNDER A PRESSURE-VOLUME GRAPH ALSO REPRESENTS WORK WHEN THE PRESSURE IS NOT CONSTANT.—Thus, if the pressure behind the piston of Fig. 251 had varied as shown by the line *ab* in Fig. 252, then the average pressure would have been 5 lb. per sq. ft. as indicated by the dashed line a_1b_1 and the work done would be represented by the shaded area of 30 ft.-lb. The finding of the work done for different variations of the pressure is shown in Figs. 253 and 254. Where

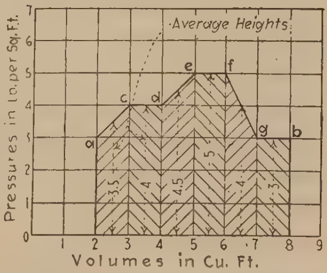


FIG. 253.—Work diagram with rising and falling pressures. Since the areas under each of the lines *ac*, *cd*, *de*, etc. are each 1 unit wide, the work done along *each* line (*ac*, *cd*, etc.) in foot-pounds is numerically equal to the average height shown. (The total work done may be computed thus: The average *height of strip ac*32 = (3 + 4) ÷ 2 = 3.5; of *cd*43 = 4; of *de*54 = (4 + 5) ÷ 2 = 4.5; of *ef*65 = 5; of *fg*76 = (5 + 3) ÷ 2 = 4; and of *gb*87 = 3. Hence, for this diagram, the *average pressure* = (3.5 + 4 + 4.5 + 5 + 4 + 3) ÷ 6 = 4 *lb. per sq. ft.* The horizontal length of the diagram indicates: *displacement volume* = 8 − 2 = 6 *cu. ft.* Hence, as indicated by the hatched area of the diagram, *work done* = *pressure* × *volume* = 4 × 6 = 24 *ft.-lb.*)

greater accuracy is required than can be obtained by using vertical strips 1 cu. ft. wide, the diagram may be divided into strips each having a width of only a fraction of 1 cu. ft. as in Fig. 255. For the greatest accuracy, a planimeter or area-measuring instrument is employed (see the author's "Steam Engine Principles and Practice" and also Sec. 503).

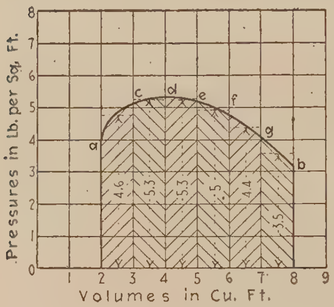


FIG. 254.—Work diagram with continuously varying pressure. The number of foot-pounds represented by each vertical strip is found exactly as in Fig. 253. As represented by the hatched area: *Total work done* = *Pressure* × *Volume* = [(4.6 + 5.3 + 5.3 + 5 + 4.4 + 3.5) ÷ 6] × (8 − 2) = 4.68 × 6 = 28.1 *ft.-lb.*

NOTE.—IN THERMODYNAMIC COMPUTATIONS, VOLUMES ARE ALWAYS, UNLESS OTHERWISE SPECIFIED, TAKEN IN CUBIC FEET AND PRESSURES IN POUNDS PER SQUARE FOOT. This is to insure that the work values which result from the computations will be in foot-pounds. Why this is true may be understood from a consideration of the following derivation.

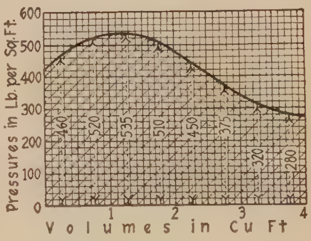


FIG. 255.—Another pressure-volume work diagram. The work diagram is divided into strips each ½ cu. ft. wide, the average height of each strip being indicated. The work represented by each strip is therefore equal to (½ the average height of the strip) ft.-lb. The total work done, which is represented by the hatched area, may be computed thus: *Average pressure* = (460 + 520 + 535 + 510 + 450 + 375 + 320 + 280) ÷ 8 = 431.25 *lb. per sq. ft. Displacement volume* = 4 *cu. ft.* Hence, *total work done* = *Pressure* × *Volume* = 431.25 × 4 = 1,725 *ft.-lb.*

263. To Compute The Work Done By The Expansion, Or In The Compression, Of A Gas Or Vapor When The Average Pressure And The Initial And Final Volumes Are Known, use the following formulas:

By expansion:

(167) $$W = P(V_2 - V_1) \quad \text{(foot-pounds)}$$

By compression:

(168, $$W = P(V_1 - V_2) \quad \text{(foot-pounds)}$$

Wherein: W = work done by the gas or vapor in expanding or done on the gas or vapor in compressing it, in foot-pounds. P = average absolute pressure exerted by (or on) the gas during its expansion (or contraction), in pounds per square foot; this is the average of *all* of the pressures—not merely the mean of the initial and the final pressures. V_2 = final volume of the gas, in cubic feet. V_1 = initial volume of the gas, in cubic feet.

EXAMPLES.—See Figs. 215, 252, 253, 254 and 255 for examples which illustrate the application of the above formula. Certain of these illustrations also show how the *average absolute pressure*, P, is computed.

DERIVATION.—When the piston (Fig. 245) stands at M, the volume of space between the piston and the cylinder head may be expressed by:—

(169) $$V_1 = AL_1$$ (cubic feet)

Wherein: V_1 = the volume, due to position M, in cubic feet. A = the area of the piston, in square feet. L_1 = the distance, due to position M, between the piston and the cylinder head, in feet. When the piston is moved to N, then the volume of space between the piston and the cylinder-head may, similarly, be expressed by:

(170) $$V_2 = AL_2$$ (cubic feet)

Wherein: V_2 = the volume, due to position N, in cubic feet. L_2 = the distance due to position N, between the piston and the cylinder head, in feet. Now, the average force exerted in moving the piston from M to N may be expressed by:—

(171) $$F = AP$$ (pounds)

Wherein: F = the average force, in pounds, exerted against the piston. P = the average pressure against the piston, in pounds per square foot. A = piston area, in square feet, as before. Now, the work which is done, due to the movement of the piston against an external force, may be expressed by:

(172) $$W = F(L_2 - L_1)$$ (foot-pounds)

Wherein: W = the work done, in foot-pounds. $(L_2 - L_1)$ = the distance through which the piston moves, in feet. F = the average pushing force, in pounds, as above. Now substituting for F in For. (172), its equivalent AP from For. (171) there results:

(173) $$W = AP(L_2 - L_1) = P(AL_2 - AL_1)$$ (foot-pounds)

Now substituting in For. 173 for AL_2 and AL_1, their equivalents V_2 and V_1 from Fors. (170) and (169), there results:

(174) $$W = P(V_2 - V_1)$$ (foot-pounds)

which is For. (167). By a similar process of reasoning For. (168) for compression may be derived.

NOTE.—THE IMAGINARY GRAPH OF Fig. 252 and certain others which immediately precede and follow, are included only to illustrate the general principle under discussion. The values obtained by the actual expansion of gases and in heat engine practice are always, as will be shown, such that that they will not plot into simple straight-line graphs.

264. The "Effective Work" Done By An Expanding Gas is equal to the *total* work minus the *back-pressure* work. The discussion of the preceding sections concerned only the total work as do most of the following sections. However, as is explained below, when a gas expands behind a piston the other side of which is subject to atmospheric or other pressure, then only a portion of the work done by the gas on the piston, is effective in doing useful work

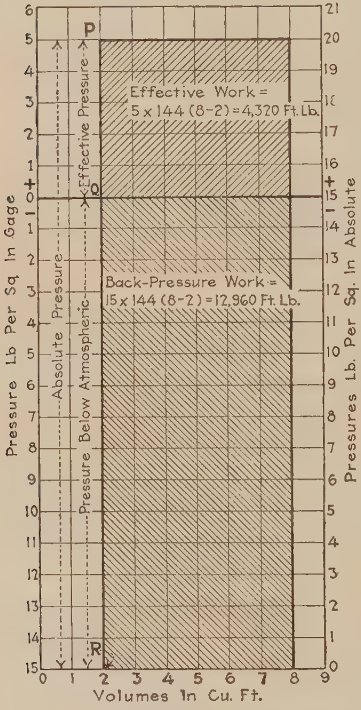


FIG. 256.—Pressure-volume diagram for gas expanding in atmosphere at 5 lb. per sq. in. gage constant pressure.

EXPLANATION.—Suppose that the piston of Fig. 251 is subjected at its right or open end to atmospheric pressure and that the pressure of the expanding gas within the cylinder remains 5 lb. per sq. in. *gage* during the expansion. Then the work diagram for the expansion will be as represented in Fig. 256. A total pressure *RP* due to the expanding gas is tending to force the piston to the right, but a pressure *RQ* is tending to force the piston to the left. The total shaded area (17,280 ft. lb.) then represents the total work done by the expanding gas but the lower portion of the area represents work done (12,960 ft.-lb.) in overcoming the resistance of the atmosphere and only the upper portion of the area (4,320 ft.-lb.) represents the work available or "effective" for overcoming additional resistances. Hence, the lower area is called the *back-pressure work*, whereas the upper area is called the *effective work*. Their sum is called the *total* work.

Note that, when the pressure is plotted in pounds per square inch, the work is found by multiplying the product of the pressure and the volume change by "144" which is the number of square inches in 1 sq. ft. Each unit of height on the graph represents a pressure of 1 lb. per sq. in. or 144 lb. per sq. ft.

265. The Specific Heat Of A Gas May Have Any Value whatsoever depending on how much work the gas is permitted to do as it is heated. See Sec. 88 for the definition of "specific heat." As was explained in Sec. 259, the heat which is added to a gas can be expended in either or both of two ways—in raising its temperature and in doing external work. Hence, the quantity of heat that must be added to each 1 lb. of a gas as its temperature is increased 1° F. (its specific heat) consists of two parts—(1) *The vibration heat.* (2) *The external-work heat.* The vibration heat is always the same for 1 lb. of a given gas heated through 1° F. but, as will be shown, the external-work heat will depend on the quantity of work that the gas is permitted to do while its temperature is being raised. Since the gas may expand in any number of ways or may be compressed while it is heated, it follows that, as above stated, the specific heat may have any value whatever. Certain principal values of the specific heats of gases will be discussed in following sections.

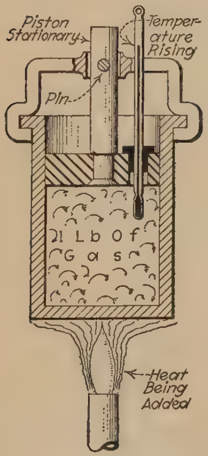


Fig. 257.—Heating a gas which cannot expand and hence can do no external work.

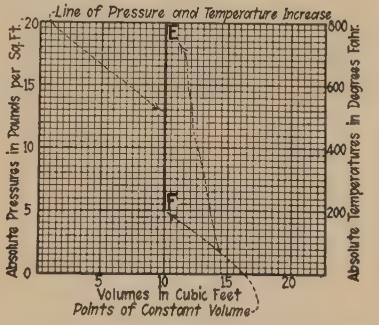


Fig. 258.—"Work diagram" for a constant-volume, pressure and temperature change—(10 cu. ft. of gas at 5 lb. per sq. ft. absolute and 200° F. absolute = 10 cu. ft. of gas at 20 lb. per sq. ft. absolute and 800° F. absolute, but no external work is done).

266. The Specific Heat Of A Gas When Its Volume Is Maintained Constant, Fig. 257, is a very useful value. It will be represented by C_V and referred to as *specific heat at constant volume.* By Charles' law (Sec. 237) the pressure of a given weight of gas, when heated in a constant volume, varies directly as its absolute temperature. Hence, the *pressure-volume graph for a constant-volume heating* is a vertical straight line *FE*, Fig. 258, under which there is no area. This is as may be expected for, when a gas does not expand its volume does not change and hence it does no work. Therefore all of the heat added to a gas at constant volume is vibration heat and is effective only in raising its temperature. The specific heats of various gases at constant volume are given in Table 251.

267. The Specific Heat Of A Gas When Its Pressure Is Maintained Constant, Fig. 259, is another very useful value.

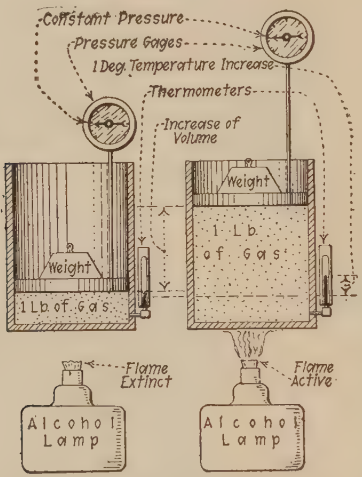


Fig. 259.—Heating a gas at constant pressure—gas expands as it is heated and does work in moving the piston upward.

It will be represented by C_P and will be referred to as *specific heat at constant pressure.* More heat is required to heat a gas through 1° F. at constant pressure than at constant volume because at constant pressure the gas expands, Fig. 259, and does external work. Enough heat must be added to increase the temperature and, besides this, the heat equivalent of the external work must also be added. It is interesting to note that for a given gas, C_P is independent of the pressure under which the gas is heated (see example below).

EXAMPLE.—If 1 lb. of air at 32° F. is confined in a volume of 1 cu. ft., it will, by For. (146), be under a pressure of 26,250 lb. per sq. ft. abs. (Fig. 260-*I*). As the air is heated at constant pressure to 132° F. its volume will increase to 1.203 cu. ft. (Fig. 260-*II*). Hence, the *external work done by the gas* = (*pressure*) × (*volume change*) = 26,250 × 0.203 = 532 *ft.-lb.* Therefore, the *heat added* = $C_V\ (T_2 - T_1) + (532/778) = 0.171 \times 100 + 0.684 = 17.784$ *B.t.u.* If, however, the 1 lb. of air at 32° F. occupied a volume of 3 cu. ft.,

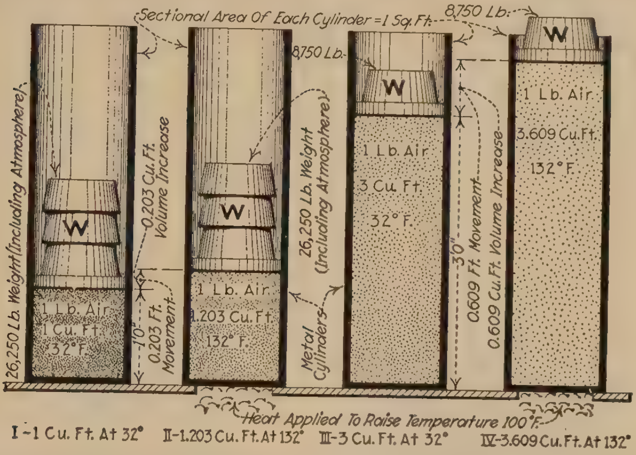

Sectional Area Of Each Cylinder = 1 Sq. Ft.
8,750 Lb.
8,750 Lb.
W
W
W
W
26,250 Lb. Weight (Including Atmosphere)
1 Lb. Air
1 Cu. Ft.
32° F.
0.203 Cu. Ft. Volume Increase
10"
0.203 Ft. Movement
1 Lb. Air
1.203 Cu. Ft.
132° F.
26,250 Lb. Weight (Including Atmosphere)
Metal Cylinders
1 Lb. Air
3 Cu. Ft.
32° F.
30"
0.609 Ft. Movement
0.609 Cu. Ft. Volume Increase
1 Lb. Air
3.609 Cu. Ft.
132° F.
Heat Applied To Raise Temperature 100° F.
I - 1 Cu. Ft. At 32°
II - 1.203 Cu. Ft. At 132°
III - 3 Cu. Ft. At 32°
IV - 3.609 Cu. Ft. At 132°

FIG. 260.—Showing how the specific heat of a gas at constant pressure is a constant for all pressures. (In each case the weight value indicated is the total weight on the gas including weight of piston and atmospheric pressure.)

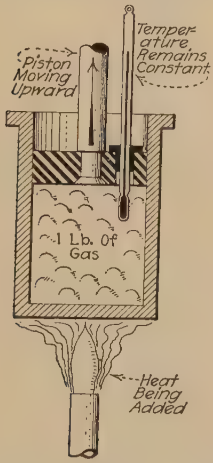


FIG. 261.—When a gas expands and is heated simultaneously at such rates that its temperature remains constant, its specific heat is infinite. See also Fig. 262.

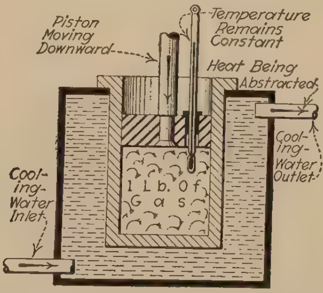


FIG. 262.—When a gas is simultaneously cooled and compressed at such rates that its temperature remains constant during the process, its specific heat is infinite.

its pressure would be 8,750 lb. per sq. ft. (Fig. 260-*III*). On being heated to 132° F. it would expand to 3.609 cu. ft. (Fig. 260-*IV*) and the *external work done* = 8,750 × 0.609 = 532 *ft.-lb.* as before. Hence 17.784 B.t.u. must have again been added in passing from *III* to *IV*.

Note.—Other Values For The Specific Heat Of A Gas May Be Found When The Pressure And Volume Of The Gas Both Vary during a change. Thus, if the gas is permitted to do external work at the same rate as that at which heat is added to it, Fig. 261, then the temperature remains constant in spite of the addition of heat (see example under Sec. 259). In such a case the specific heat is infinite for, no matter how much heat is added, the temperature does not rise. (See also Fig. 262.) Furthermore, if a gas is compressed while no heat is added or abstracted from it, Fig. 263, then its temperature will rise. Thus, no heat is required to effect the temperature rise and the specific heat is zero. Furthermore, a gas may be heated and expanded at such rates (Fig. 264) that its temperature actually decreases. In such a case more work is done than the equivalent of the heat energy added to the gas; the specific heat is negative because the temperature decreases in spite of a heat addition. So it is evident that the specific heat of a gas may have any value whatsoever.

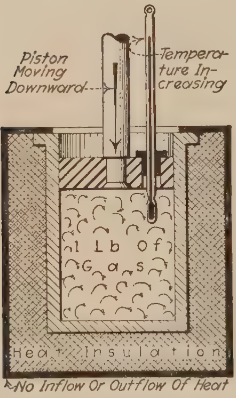


Fig. 263.—Specific heat is zero when a gas is compressed without loss or gain of heat (adiabatic compression).

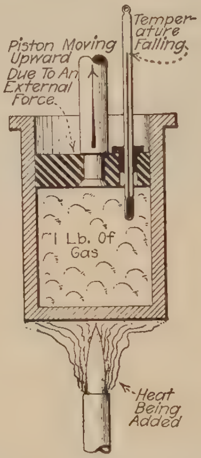


Fig. 264.—When a gas is heated and expanded simultaneously at such rates that the temperature is decreased, the specific heat is negative.

268. The Energy Relations During Condition Changes Of Perfect Gases will now be considered. These energy relations are important principally in the study of gas cycles (Div. 12) for, as will be shown, all gas cycles are made up of a number of condition changes. The condition changes which gases undergo in actual gas cycles are principally those during which the specific heat of the gas has a constant value. Although condition changes are frequently spoken of as *expansions* and *compressions*, there is one form of condition change which is neither an expansion nor a compression—that is, the *constant-volume change.* Hence, the terms expansion and contraction should only be used for such condition changes during which the volume of the gas is actually changed.

NOTE.—CONDITION CHANGES MAY OCCUR IN ANY MANNER—in an infinite number of ways. The condition changes of which gas cycles are considered as being ideally composed (Div. 12) are, however, such as occur when some property of the gas, such as its volume, pressure, temperature, or specific heat remains constant, or when no heat is transferred to or from the gas. As will be shown, in all of these cases the specific heat may be considered as having some constant value during the change—different for each change. Hence, broadly, the changes here discussed are all constant-specific-heat changes. Furthermore, during the changes here treated all of the volume of the gas is to be considered as being at the same pressure and temperature, as would occur when the gas is confined in a cylinder whose volume is varied by a movable piston. *Changes which a gas undergoes when a portion of it exists at a higher pressure or temperature than some other portion,* do not follow the laws here given. Such changes would occur when a gas is partly confined in one vessel at a high pressure and the remainder is in another vessel at a lower pressure, the two vessels being connected by a small opening through which the gas is flowing. In such a case there is always more or less throttling (note under Sec. 260) or internal friction in the gas —the following discussion does not apply to such frictional processes. Changes which occur in heat-engine cylinders are always practically "frictionless;" that is, they occur with practically no internal friction.

NOTE.—THE ALGEBRAIC SIGNS OF ENERGY QUANTITIES FOR GASES WILL BE DETERMINED THUS: (1) *Heat* (Q) is considered positive when it is added to a gas; negative when it is abstracted from the gas. (2) *External work* (W_E) is considered positive when the gas expands; negative when the gas is compressed—when external work is done *on* the gas. (3) *Vibration work* (W_V) is considered positive when the temperature of the gas is raised; negative when the temperature of the gas is lowered.

269. The Energy Relations During A Condition Change At Constant Volume—An Isometric Change—are quite simple. By the definition of specific heat at constant volume (Sec. 266) the heat exchange to or from the gas is the product of the weight, temperature change, and specific heat at constant volume of the gas—see For. (175) below. Now, since during a constant-volume change no external work is done (Fig. 258), all of the heat added to or abstracted from the gas is effective in changing the temperature of the gas—that is, in doing vibration work. The formulas for these relations are:

(175) $$\mathbf{Q} = \mathbf{WC}_V(T_2 - T_1) \qquad \text{(B.t.u.)}$$

(176) $$W_E = 0 \qquad \text{(external work)}$$

By multiplying For. (175) by "778," which is the number of foot-pounds in 1 B.t.u., there results:

(177) $$W_V = 778\mathbf{WC}_V(T_2 - T_1) \qquad \text{(foot-pounds)}$$

Wherein: $\mathbf{Q}$ = the heat added to the gas, in British thermal units. $\mathbf{W}$ = the weight of the gas, in pounds. $\mathbf{C}_V$ = the specific heat of the gas at constant volume; see Table 251. T_2 and T_1 = respectively, the final and initial temperatures of the gas in degrees Fahrenheit. W_E = the external work done by the gas. W_V = the vibration work done by the gas, in foot-pounds. See notes under Sec. 268 concerning the algebraic signs of the energy quantities and also as to the manner in which the changes are assumed to occur.

Note.—Practical Examples Of Isometric Changes may be stated thus: (1) *The heating or cooling of a given weight of gas which is enclosed in a strong tank or receiver.* (2) *The heating (explosion) of a gaseous mixture in an internal-combustion-engine* (Otto-cycle, Div. 12) *cylinder;* this process actually differs slightly from a strict isometric change because it is accompanied by a change in chemical composition of the gas—but it is often considered as an isometric condition change, see example below. The volume of the gases in the cylinder remains practically constant during the very short time interval occupied by the explosion.

Example.—Suppose that an internal-combustion-engine cylinder contains ⅕ lb. of gas at 120° F. and that this gas is ignited by an electric spark. What will be the final temperature if 65.8 B.t.u. are liberated by the explosion and if $\mathbf{C}_V$ for the mixture remains approximately 0.175 throughout the process? Solution.—By transposing For. (175), there results: $T_2 = (\mathbf{Q}/\mathbf{WC}_V) + T_1 = [65.8 \div (0.2 \times 0.175)] + 120 = 2{,}000°\ F.$

Example.—If 1 lb. of a perfect gas is heated at constant volume through 1° F., Fig. 265, and if the specific heat of the gas at constant volume is 0.30, what quantity of heat is added, and what amounts of external work and work in raising the temperature (vibration work) are done? SOLUTION.—By For. (175), the *heat added* = $Q = WC_V(T_2 - T_1) = 1 \times 0.30 \times 1 = 0.30$ *B.t.u.* By For. (176), the *external work* = $W_E = 0$. By For. (177), the *vibration work* = $W_V = 778WC_V(T_2 - T_1) = 778 \times 0.30 = 233.4$ *ft.-lb.*

EXAMPLE.—How much heat is added to 8 lb. of oxygen contained in a strong tank in raising its temperature from 70° F. to 500° F. (the volume of gas kept constant during the heating)? How much external work is done and how much work in raising the temperature (vibration work)? SOLUTION.—From Table 251, C_V for oxygen is 0.155. Hence, by For. (175), the *heat added* = $Q = WC_V(T_2 - T_1) = 8 \times 0.155(500 - 70) = 533.2$ *B.t.u.* By For. (176), the *external work* = $W_E = 0$. By For. (177), the vibration work = $W_V = 778WC_V(T_2 - T_1) = 778 \times 533.2 = 414{,}829.6$ *ft.-lb.*

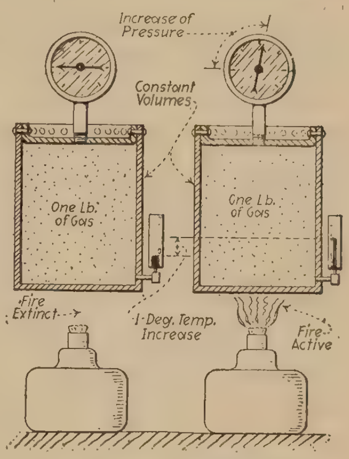


FIG. 265.—Specific heat at constant volume is 0.30. What are the energy relations?

270. The Energy Relations During A Condition Change At Constant Pressure—An Isobaric Change—are given by the following formulas which are derived as shown below:

$$Q = WC_P(T_2 - T_1) \quad \text{(B.t.u.)} \tag{178}$$

$$W_E = P(V_2 - V_1) \quad \text{(ft.-lb.)} \tag{179}$$

or

$$W_E = 778W(C_P - C_V)(T_2 - T_1) \quad \text{(ft.-lb.)} \tag{180}$$

$$W_E = Wk_G(T_2 - T_1) \quad \text{(ft.-lb.)} \tag{181}$$

$$W_V = 778WC_V(T_2 - T_1) \quad \text{(ft.-lb.)} \tag{182}$$

Wherein: Q = the heat added to the gas, in British thermal units. W = the weight of the gas, in pounds. T_2 and T_1 = respectively, the final and initial temperatures of the gas, in degrees Fahrenheit. W_E = the external work done by the gas, in foot-pounds. P = the pressure exerted by the gas during the change, in pounds per square *foot* absolute. V_2 and V_1 = respectively, the final and initial volumes of the gas, in cubic feet. C_p and C_V = respectively, the specific heats of the gas at constant pressure and at constant volume; for values see Table 251. k_G = the gas constant (Sec. 247). W_V = the vibration work done on the gas, in foot-pounds. See the notes under Sec. 268 regarding the algebraic signs of the energy quantities and also as to the manner in which the changes are assumed to occur.

DERIVATION.—By the definition of the specific heat at constant pressure (Sec. 267), the quantity of heat added to the gas is as shown by For. (178). Also, by Sec. 263, the work done during a constant-pressure expansion is equal to the pressure times the volume change—as shown by For. (179). Now, the vibration work done on a gas depends only on its weight and temperature change. Hence, for a given weight of any gas, when heated through a given temperature range, the vibration work will be the same regardless of how the pressure and volume vary. Therefore, *the vibration work for all condition changes*, is as given by For. (177) which is the same as For. (182). Since, for a perfect gas, the heat added is effective in doing only vibration and external work (Sec. 259),

$$778\mathrm{Q} = W_V + W_E \qquad \text{(ft.-lb.)} \tag{183}$$

or, transposing:

$$W_E = 778\mathrm{Q} - W_V \qquad \text{(ft.-lb.)} \tag{184}$$

Now, substituting in For. (184) from Fors. (178) and (182), there results

$$W_E = 778\mathrm{WC}_P(T_2 - T_1) - 778\mathrm{WC}_V(T_2 - T_1) \qquad \text{(ft.-lb.)} \tag{185}$$

which simplifies to the form of For. (180).

By the general gas law, For. (145), $PV_1 = \mathrm{W}k_G\mathrm{T}_1$ and $PV_2 = \mathrm{W}k_G\mathrm{T}_2$. Also, For. (179), when expanded becomes:

$$W_E = PV_2 - PV_1 \qquad \text{(ft.-lb.)} \tag{186}$$

Now, substituting in For. (186), the values from For. (145), there results,

$$W_E = \mathrm{W}k_G\mathrm{T}_2 - \mathrm{W}k_G\mathrm{T}_1 \qquad \text{(ft.-lb.)} \tag{187}$$

or, simplifying:

$$W_E = \mathrm{W}k_G(\mathrm{T}_2 - \mathrm{T}_1) \qquad \text{(ft.-lb.)} \tag{188}$$

But, it is a fact that:

$$\mathrm{T}_2 - \mathrm{T}_1 = T_2 - T_1 \qquad \text{(deg. fahr.)} \tag{189}$$

Hence,

$$W_E = \mathrm{W}k_G(T_2 - T_1) \qquad \text{(ft.-lb.)} \tag{190}$$

which is the same as For. (181).

NOTE.—PRACTICAL APPLICATIONS OF ISOBARIC CHANGES are: (1) *The heating or cooling of a gas which is under constant pressure such as atmospheric pressure and which is not wholly confined*—as, for example, the gas in a balloon, the combustion gases in a boiler furnace, or the air which cools an automobile radiator. (2) *The expansion in an oil engine while* *the charge of oil is burned in the cylinder as the piston moves in the cylinder*—this expansion is only sometimes isobaric, it may be quite different; this is not strictly a condition change because it is accompanied by a chemical change in the gases.

EXAMPLE.—How much heat is added to each 100 lb. of air which passes through a boiler furnace as its temperature is increased from 70° F. to 500° F.? SOLUTION.—By Table 251, for air, $C_P = 0.241$. Hence, by For. (178), the *heat added* $= Q = WC_P(T_2 - T_1) = 100 \times 0.241 \times (500 - 70) = 10{,}350$ *B.t.u.*

EXAMPLE.—How much heat must be added to 5 lb. of nitrogen to increase its volume from 45 cu. ft. to 100 cu. ft. at the constant pressure of 25 lb. per sq. in. abs.? How much external work is done by the expanding gas and how much (vibration) work is done in raising the temperature? SOLUTION.—For nitrogen, the value of k_G is, by Table 251, 54.99. Also, $C_P = 0.247$ and $C_V = 0.176$. The *initial temperature* of the gas is, by For. (148), $T_1 = PV_1/Wk_G = (25 \times 144) \times 45 \div (5 \times 54.99) = 498°$ *F. abs.* or 38° *F.* The *final temperature* $= T_2 = (25 \times 144) \times 100 \div (5 \times 54.99) = 1{,}309°$ *F. abs.* or 849° *F.* Hence, by For. (178), the *heat added* $= WC_P(T_2 - T_1) = 5 \times 0.247(849 - 38) = 1001.6$ *B.t.u.* By For. (179), the *external work* $= W_E = P(V_2 - V_1) = (25 \times 144)(100 - 45) = 198{,}000$ *ft.-lb.* By For. (182), $W_V = 778WC_V(T_2 - T_1) = 778 \times 5 \times 0.176(849 - 38) = 555{,}243$ *ft.-lb.*

EXAMPLE.—If 3 lb. of oxygen is expanded at constant pressure by increasing the temperature from 85° F. to 100° F. (Figs. 266 and 267), find how much heat is added, how much external work is done, and how much (vibration) work is done in raising the temperature. SOLUTION.— From Table 251, the following values are found for oxygen: $C_P = 0.217$. $C_V = 0.155$. $k_G = 48.25$. Hence, by For. (178), the *heat added* $= Q = WC_P(T_2 - T_1) = 3 \times 0.217 \times (100 - 85) =$

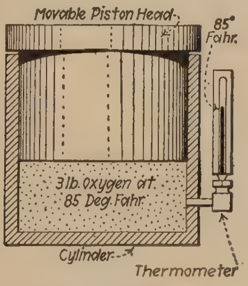


FIG. 266.—Oxygen gas (3 lb. at 85° F.) ready to be expanded under constant pressure.

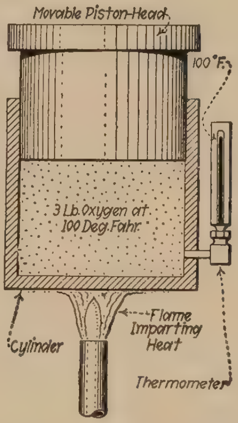


FIG. 267.—Conditions after the expansion of 3 lb. of oxygen gas under constant pressure by heating from 85° F. to 100° F.

9.765 *B.t.u.* Also, by For. (181), the *external work* = $W_E = \mathrm{W}k_G(T_2 - T_1) = 3 \times 48.25 \times (100 - 85) = 2{,}171.25$ *ft.-lb.* And, by For. (182), the *vibration work* = $W_V = 778\mathrm{W}\mathrm{C}_V(T_2 - T_1) = 778 \times 3 \times 0.155 \times (100 - 85) = 5{,}426.55$ *ft.-lb.*

Example.—Assume that 10 cu. ft. of a certain gas at 32° F. exerts a pressure of 10 lb. per sq. ft. abs. (Fig. 268). Compare the external work done in expanding the gas at constant pressure to 15 cu. ft. with that done by compressing the gas at constant pressure to 5 cu. ft. Solution.—In expanding the gas, by For. (179), the *external work* = $W_E = P(V_2 - V_1) = 10(15 - 10) = 50$ *ft.-lb.* In compressing the gas, the *external work* = $W_E = P(V_2 - V_1) = 10(5 - 10) = -50$ *ft.-lb.* The negative sign indicates that work is done *on* the gas. Thus, *numerically* the same amount of work is done in the two cases—as is shown by the equal areas A and B in Fig. 268.

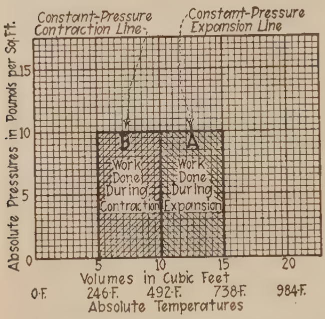


Fig. 268.—Work diagram showing constant-pressure expansion and contraction (10 cu. ft. of gas at 10 lb. per sq. ft. absolute, and 492° F. absolute = 15 cu. ft. of gas at 10 lb. per sq. ft. absolute, and 738° F. absolute = 5 cu. ft. of gas at 10 lb. per sq. ft. absolute, and 246° F. absolute).

271. The Energy Relations During A Condition Change At Constant Temperature—An Isothermal Change—may be found by the following formulas which are derived as shown below. The pressure-volume relations for an isothermal change are governed by Boyle's law, For. (108).

(191) $$W_E = P_1V_1 \log_e \frac{V_2}{V_1} \qquad \text{(ft.-lb.)}$$

(192) $$W_E = P_1V_1 \log_e \frac{P_1}{P_2} \qquad \text{(ft.-lb.)}$$

(193) $$W_E = \mathrm{W}k_G\mathrm{T} \log_e \frac{V_2}{V_1} \qquad \text{(ft.-lb.)}$$

(194) $$\mathbf{Q} = \frac{W_E}{778} \qquad \text{(B.t.u.)}$$

(195) $$W_V = 0 \qquad \text{(work)}$$

Wherein: **Q** = the heat added to the gas, in British thermal units. P_1 and P_2 = respectively, the initial and final pressures of the gas, in pounds per square foot absolute. V_1 and V_2 = respectively, the initial and final volumes of the gas, in cubic feet. **W** = the weight of the gas, in pounds. k_G = the gas constant (Sec. 247). **T** = the temperature of the gas, in degrees Fahrenheit *absolute*. W_E = the external work done by the gas, in foot-pounds. W_V = the vibration work done on the gas. $\log_e$ = the natural logarithm of the number following the symbol. The natural logarithm of a number is approximately 2.303 times the common logarithm of the same number. See the notes under Sec. 268 regarding the algebraic signs of the energy quantities and also as to the manner in which the changes are assumed to occur.

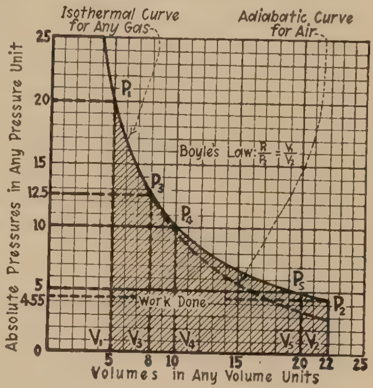


FIG. 269.—Isothermal or constant-temperature expansion graph.

DERIVATION.—Since, during an isothermal change, the temperature remains constant, none of the heat added is effective in doing vibration work. This may also be shown by placing $T_2 = T_1$ in For. (177) which, as has been stated, applies to *any* condition change. This relation is stated by For. (195). Now, For. (166) states that, for any heat transfer:

$$Q = Q_V + Q_D + Q_E \qquad \text{(B.t.u.)} \tag{196}$$

Hence, since for a perfect gas $Q_D = 0$ (as proved under Sec. 258) and since for an isothermal change $Q_V = 0$, For. (196) becomes:

$$Q = Q_E \qquad \text{(B.t.u.)} \tag{197}$$

and, since $Q_E = W_E/778$:

$$Q = \frac{W_E}{778} \qquad \text{(B.t.u.)} \tag{198}$$

which is the same as For. (194).

Now, the pressure-volume graph of an isothermal change is a curved line (Fig. 269). For a change from P_1, V_1 to P_2, V_2, the area under the graph (the shaded area in Fig. 269) is found by the calculus to be expressed by the formula:

$$Area = P_1V_1 \log_e \frac{V_2}{V_1} \qquad \text{(area units)} \tag{199}$$

If, now, the pressures are expressed in pounds per square foot and the volumes in cubic feet, the area will represent the work done, in foot-pounds, as expressed by For. (191).

For. (192) results from For. (191) by substituting for V_2/V_1 its equivalent from For. (108). For. (193) results from For. (191) by substituting for P_1V_1 its equivalent from For. (145). These substitutions may suggest to the reader still different ways of expressing For. (191).

Note.—There Are No Practical Applications Of Isothermal Gas Changes.—The nearest approach to such a change would probably occur in an air compressor. In this machine water, which is circulated through a jacket surrounding the cylinder, carries away a large part of the heat which is developed by the work done on the air in compressing it. Isothermal changes are of value, however, because they constitute the *ideal compression* for air and other gas compressors and hence afford a goal in compressor design.

Example.—If a certain gas exerts a pressure of 100 lb. per sq. ft. abs. when confined in a volume of 5 cu. ft. and is expanded isothermally to a volume of 22 cu. ft., how much external work is done and how much heat must have been added during the process? Solution.—By For. (191), the *external work* $= W_E = P_1V_1 \log_e(V_2/V_1) = 100 \times 5 \times \log_e(22 \div 5) = 500 \times \log_e 4.4$. From tables of logarithms, the *common logarithm* of $4.4 = \log 4.4 = 0.643$. Hence, $\log_e 4.4 = 2.303 \times 0.643 = 1.479$. Hence, $W_E = 500 \times 1.479 = 739.5$ *ft.-lb.* By For. (194), the *heat added* $= Q = W_E/778 = 739.5 \div 778 = 0.95$ *B.t.u.*

Example.—How much external work is done when 6 lb. of hydrogen is compressed at the constant temperature of 70° F. from a volume of 144 cu. ft. to a final volume of 12 cu. ft.? How much heat must be abstracted? Solution.—By Table 251, for hydrogen, $k_G = 765.9$. By For. (193), the *external work* $= W_E = Wk_G \log_e(V_2/V_1) = 6 \times 765.9 \times \log_e(12 \div 144) = 4{,}595.4 \times \log_e(1/12)$. From a table of logarithms the *common logarithm* of $1/12 = \log(1/12) = -1.079$. Hence $\log_e(1/12) = 2.303 \times (-1.079) = -2.482$. Hence, $W_E = 4{,}595.4 \times (-2.482) = -11{,}406$ *ft.-lb.* Hence, 11,406 ft.-lb. of work must be done *on* the gas. By For. (194), the *heat added* $= Q = W_E/778 = -11{,}406 \div 778 = -14.66$ *B.t.u.* Hence, 14.66 B.t.u. must be *abstracted.*

272. The Energy Relations During A Condition Change Which Involves No Heat Transfer—A Frictionless Adiabatic Change (which is the same as an isentropic change, Sec. 385), (Figs. 270 and 271)—may be found by the following formulas which are derived below. The pressure-volume relations for and adiabatic change (Sec. 275) are based on these energy relations.

$$(200) \qquad Q = 0 \qquad \text{(heat)}$$

$$(201) \qquad W_E = \frac{P_1V_1 - P_2V_2}{k - 1} \qquad \text{(ft.-lb.)}$$

$$(202) \qquad W_E = 778WC_V(T_1 - T_2) \qquad \text{(ft.-lb.)}$$

$$(203) \qquad W_V = -W_E \qquad \text{(ft.-lb.)}$$

$$(204) \qquad W_V = 778WC_V(T_2 - T_1) \qquad \text{(ft.-lb.)}$$

Wherein: $\mathbf{Q}$ = the heat added during the change. W_E = the external work done by the gas, in foot-pounds. P_1 and P_2 = respectively, the initial and final pressures exerted by the gas, in pounds per square foot absolute. V_1 and V_2 = respectively, the initial and final volumes of the gas, in cubic feet. $\mathbf{k}$ = the ratio $(\mathbf{C}_P/\mathbf{C}_V)$ of the specific heats of the gas at constant pressure and constant volume; values of $\mathbf{k}$ are given in Table 251. $\mathbf{C}_V$ = the specific heat of the gas at constant volume; Table 251. T_1 and T_2 = respectively, the initial and final temperatures of the gas, in degrees Fahrenheit. W_V = the vibration work done on the gas, in foot-pounds. See notes under Sec. 268 concerning the algebraic signs of the energy quantities, and concerning frictional processes.

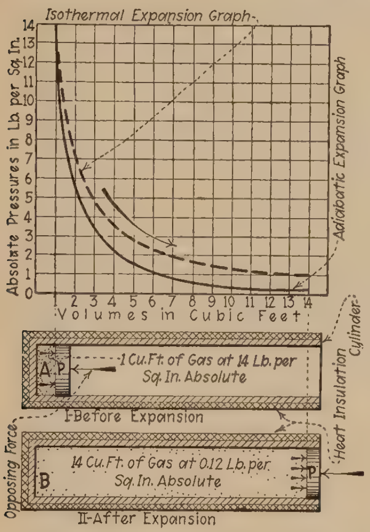

Isothermal Expansion Graph
Adiabatic Expansion Graph
Absolute Pressures in Lb. per Sq. In.
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14
1 2 3 4 5 6 7 8 9 10 11 12 13 14
Volumes in Cubic Feet
Cylinder
Heat Insulation
A
P
1 Cu. Ft. of Gas at 14 Lb. per Sq. In. Absolute
I-Before Expansion
Opposing Force
B
14 Cu. Ft. of Gas at 0.12 Lb. per Sq. In. Absolute
P
II-After Expansion

FIG. 270.—Adiabatic gas expansion—when heat can neither enter nor leave the gas through the confining surfaces.

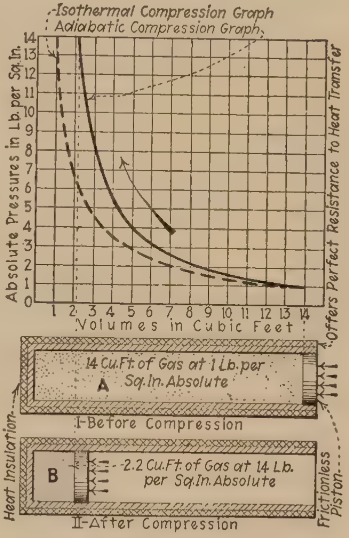

Isothermal Compression Graph
Adiabatic Compression Graph
Absolute Pressures in Lb. per Sq. In.
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14
1 2 3 4 5 6 7 8 9 10 11 12 13 14
Volumes in Cubic Feet
Offers Perfect Resistance to Heat Transfer
14 Cu. Ft. of Gas at 1 Lb. per Sq. In. Absolute
A
I-Before Compression
Heat Insulation
B
2.2 Cu. Ft. of Gas at 14 Lb. per Sq. In. Absolute
II-After Compression
Frictionless Piston

FIG. 271.—Adiabatic gas compression—when heat can neither enter nor leave the gas, as heat, through the confining surfaces.

DERIVATION.—By the definition of an adiabatic process, there is no heat transfer between the gas and any external body. This statement is stated algebraically by For. (200). Also, For. (204) has been shown (Sec. 270) to hold for *any* condition change. Now, substituting in For. (196), the values $\mathbf{Q} = 0$, and $\mathbf{Q}_D = 0$, there results:

(205) $$\mathbf{Q}_E = -\mathbf{Q}_V$$ (B.t.u.)

Hence, it follows that:

(206) $$W_E = -W_V \qquad \text{(ft.-lb.)}$$

which is the same as For. (203). Substituting in For. (206) the value of W_V from For. (204), there results For. (202).

By For. (145) transposed,

(207) $$\mathbf{W}\mathrm{T}_1 = \frac{P_1V_1}{k_G}$$

and

(208) $$\mathbf{W}\mathrm{T}_2 = \frac{P_2V_2}{k_G}$$

Now, For. (202) may be written thus:

(209) $$W_E = 778\mathrm{C}_V(\mathbf{W}\mathrm{T}_1 - \mathbf{W}\mathrm{T}_2) \qquad \text{(ft.-lb.)}$$

Which becomes, by substituting from Fors. (207) and (208):

(210) $$W_E = \frac{778\mathrm{C}_V}{k_G}(P_1V_1 - P_2V_2) \qquad \text{(ft.-lb.)}$$

Now, by comparing Fors. (180) and (181), it is evident that

(211) $$k_G = 778(\mathrm{C}_P - \mathrm{C}_V)$$

Hence,

(212) $$\frac{778}{k_G} = \frac{1}{\mathrm{C}_P - \mathrm{C}_V}$$

Or, by multiplying For. (212) by C_V

(213) $$\frac{778\mathrm{C}_V}{k_G} = \frac{\mathrm{C}_V}{\mathrm{C}_P - \mathrm{C}_V}$$

or,

(214) $$\frac{778\mathrm{C}_V}{k_G} = \frac{1}{\frac{\mathrm{C}_P}{\mathrm{C}_V} - 1}$$

If the fraction $\frac{\mathrm{C}_P}{\mathrm{C}_V}$ is denoted by k, then For. (214) becomes:

(215) $$\frac{778\mathrm{C}_V}{k_G} = \frac{1}{\mathrm{k} - 1}$$

Substituting this in For. (210), there results:

(216) $$W_E = \frac{1}{\mathrm{k} - 1}(P_1V_1 - P_2V_2) \qquad \text{(ft.-lb.)}$$

which is the same as For. (201).

NOTE.—OCCURRENCES OF ADIABATIC CHANGES IN PRACTICE are, strictly speaking, never found. Quite close approaches to adiabatic processes are, however, found in: (1) *Internal-combustion engines.* (2) *Air and other gas compressors;* the compressions in these machines are generally more nearly adiabatic than they are isothermal, Sec. 271. (3) *Compressed-air engines.* Adiabatic expansions are the *ideal* expansions (see Div. 12) for heat engines.

EXAMPLE.—How much work is done by carbon-monoxide gas in expanding adiabatically from a pressure of 100 lb. per sq. in. abs. and a volume of 5 cu. ft. to a pressure of 20 lb. per sq. in. abs. and a volume of 15.6 cu. ft.? SOLUTION.—By Table 251, the value of k_G for carbon monoxide is 1.41. Hence, by For. (201), the *external work* = W_E = $(P_1V_1 - P_2V_2)/\mathrm{k} - 1$ = [(144 × 100 × 5) − (144 × 20 × 15.6)] ÷ (1.41 − 1) = (72,000 − 44,920) ÷ 0.41 = 65,270 *ft.-lb.*

EXAMPLE.—How much work is done in compressing 7 lb. of acetylene adiabatically from 70° F. to 300° F.? SOLUTION.—By Table 251, the value of C_V for acetylene is 0.270. Hence, by For. (202), the *external work* = $W_E = 778\mathrm{WC}_V(T_1 - T_2) = 778 \times 7 \times 0.270 \times (70 - 300) =$ −374,530 *ft.-lb.* Or, 374.530 ft.-lb. must be *expended* in compressing the gas.

273. The Energy Relations, Accompanying A Condition Change During Which The Specific Heat Has Any Constant Value—A Polytropic Change—may be found by the following formulas which are derived below. The pressure-volume relations for a polytropic change (Sec. 275) are based on these relations.

(217) $$\mathrm{Q} = \mathrm{WC}(T_2 - T_1) \qquad \text{(B.t.u.)}$$

(218) $$W_E = \frac{P_1V_1 - P_2V_2}{n - 1} \qquad \text{(ft.-lb.)}$$

(219) $$W_E = 778\mathrm{W}(\mathrm{C} - \mathrm{C}_V)(T_2 - T_1) \qquad \text{(ft.-lb.)}$$

(220) $$W_V = 778\mathrm{WC}_V(T_2 - T_1) \qquad \text{(ft.-lb.)}$$

Where,

(221) $$n = \frac{\mathrm{C} - \mathrm{C}_P}{\mathrm{C} - \mathrm{C}_V} \qquad \text{(a constant)}$$

(222) $$\mathrm{C} = \frac{n - \mathrm{k}}{n - 1}\mathrm{C}_V \qquad \text{(specific heat)}$$

Wherein: **Q** = the heat added to the gas, in British thermal units. **W** = the weight of the gas, in pounds. **C** = the specific heat of the gas during the process. T_1 and T_2 = respectively, the initial and final temperatures of the gas, in degrees Fahrenheit. P_1 and P_2 = respectively, the initial and final pressures of the gas, in pounds per square foot absolute. V_1 and V_2 = respectively, the initial and final volumes of the gas, in cubic feet. W_E = the external work done by the gas, in foot-pounds. W_V = the vibration work done on the gas, in foot-pounds. n = a constant defined by For. (221). C_P and C_V = respectively the specific heats of the gas at constant pressure and constant volume. **k** = the ratio C_P/C_V. See notes under Sec. 268 concerning the algebraic signs of the energy quantities and also as to the manner in which the changes are assumed to occur.

Derivation.—The specific heat (C) is, by definition (Sec. 88), the number of British thermal units which must be added to 1 lb. of a substance in order to raise its temperature through 1° F. Hence, to raise the temperature of W lb. of gas through $(T_2 - T_1)°$ F., there must be added $WC(T_2 - T_1)$ B.t.u. as expressed by For. (217). Also, For. (220) expresses the quantity of vibration work done during *any* condition change. By Sec. 259, the added heat is always effective only in doing vibration work and external work. Hence,

(223) $$W_E = 778Q - W_V \qquad \text{(ft.-lb.)}$$

Or, substituting from Fors. (217) and (220) and simplifying, there results:

(224) $$W_E = 778W(C - C_V)(T_2 - T_1) \qquad \text{(ft.-lb.)}$$

which is the same as For. 219. This For. (224) may also be written:

(225) $$W_E = 778W(C_V - C)(T_1 - T_2) \qquad \text{(ft.-lb.)}$$

or,

(226) $$W_E = 778(C_V - C)(WT_1 - WT_2) \qquad \text{(ft.-lb.)}$$

But, substituting from Fors. (207) and (208),

(227) $$W_E = \frac{778(C_V - C)}{k_G}(P_1V_1 - P_2V_2) \qquad \text{(ft.-lb.)}$$

Now, since $\mathbf{k} = C_P \div C_V$, For. 222 may be written:

(228) $$C = \frac{nC_V - C_P}{n - 1}$$

Or, subtracting both sides from C_V,

(229) $$C_V - C = \frac{C_P - C_V}{n - 1}$$

Also, by For. (211),

(230) $$k_G = 778(C_P - C_V)$$

Therefore, by substituting Fors. (229) and (230) into For. (227) there results:

(231) $$W_E = \frac{P_1V_1 - P_2V_2}{n - 1} \qquad \text{(ft.-lb.)}$$

which is the same as For. (218).

Note.—Occurrences Of Polytropic Changes In Practice are many. In practically all reciprocating machines, wherein gases are employed, the expansions and compressions of the gases are, for all practical purposes, polytropic. Actually, the specific heat probably varies somewhat during all gas expansions and compressions but, because of the short time interval which is generally consumed in one of these processes, the variation in any case is quite small.

Example.—If 1.5 lb. of hydrogen is compressed polytropically from 15 lb. per sq. in. abs. to 500 lb. per sq. in. abs. at which pressures its volumes are 200 cu. ft. and 10.76 cu. ft. respectively, how much heat is added, external work done, and vibration work? The value of n is 1.2. Solution.—For hydrogen, by Table 251, $\mathbf{C}_V = 2.44$, $k_G = 765.9$, and $\mathbf{k} = 1.40$. By For. (222), the *specific heat* $= \mathbf{C} = [(n - \mathbf{k})/(n - 1)] \times \mathbf{C}_V = [(1.2 - 1.40) \div (1.2 - 1)] \times 2.44 = (-0.20 \div 0.2) \times 2.44 = -2.44$. Hence, by For. (218), the *external work* $= W_E = (P_1V_1 - P_2V_2)/(n - 1) = [(15 \times 144 \times 200) - (500 \times 144 \times 10.76)] \div (1.2 - 1) = (432{,}000 - 774{,}720) \div 0.2 = -1{,}713{,}600$ *ft.-lb.* By For. (148), $\mathbf{T}_1 = P_1V_1/\mathbf{W}k_G = (144 \times 15 \times 200) \div (1.5 \times 765.9) = 376°$ *F. abs.* Also, $\mathbf{T}_2 = P_2V_2/\mathbf{W}k_G = (144 \times 500 \times 10.76) \div (1.5 \times 765.9) = 764.3°$ *F. abs.* Hence, by For. (217), the *heat added* $= \mathbf{WC}(T_2 - T_1) = 1.5 \times (-2.44) \times (764.3 - 376) = -1{,}420.01$ *B.t.u.* and, by For. (220), the *vibration work* $= W_V = 778\mathbf{WC}_V(T_2 - T_1) = 778 \times 1.5 \times 2.44 \times (764.3 - 376) = 1{,}105{,}676$ *ft.-lb.*

Example.—If, in an air engine, 7 lb. of air expand in such a manner that $n = 1.1$ and the temperature is reduced from 100° F. to 40° F., how much heat is added or abstracted, how much external work is done, and how much (vibration) work in reducing the temperature? Solution.—From Table 251, for air, $\mathbf{C}_P = 0.241$, $\mathbf{C}_V = 0.171$, and $\mathbf{k} = 1.40$. Hence, by For. (222), the *specific heat* $= \mathbf{C} = [(n - \mathbf{k})/(n - 1)]\ \mathbf{C}_V = [(1.1 - 1.40) \div (1.1 - 1)] \times 0.171 = -0.533$. Therefore, by For. (217) the *heat added* $= \mathbf{Q} = \mathbf{WC}(T_2 - T_1) = 7 \times (-0.533) \times (40 - 100) = 223.9$ *B.t.u.* Hence, 223.9 B.t.u. must be added. By For. (219), the *external work* $= W_E = 778\mathbf{W}(\mathbf{C} - \mathbf{C}_V)(T_2 - T_1) = 778 \times 7 \times (-0.533 - 0.171) \times (40 - 100) = 230{,}000$ *ft.-lb.* By For. (220), the *vibration work* $= W_V = 778\ \mathbf{WC}_V(T_2 - T_1) = 778 \times 7 \times 0.171 \times (40 - 100) = -55{,}900$ *ft.-lb.*

274. A Table Of Values Of The Polytropic Exponent n For Actual Machines is given below.—Since, by For. (221), n varies with the specific heat of the gas during a process, and since (Sec. 265) the specific heat may have any value whatsoever, it follows that n may also have any value whatsoever. In actual machines, however, the values of n generally have some value intermediate between 1 and $\mathbf{k}$—that is, the expansion or compression is intermediate between isothermal and adiabatic depending on the design and operation of the machine. The following values have been determined by experiment:

Type of machine	Value of n	Authority
Air compressor—cooling by injection of water	1.26–1.36	Ennis—"Applied Thermodynamics"
Air compressor—cooling by water jacket	seldom below 1.30	Ennis—"Applied Thermodynamics"
Hydraulic piston air compressors	1.23–1.28	Ennis—"Applied Thermodynamics"
Gas engines expansion, large engines	1.25	Ennis—"Applied Thermodynamics"
Gas engines expansion, small engines	1.38	Ennis—"Applied Thermodynamics"
Gas engines expansion, occasionally as high as	1.55	Ennis—"Applied Thermodynamics"
Air compressors, water jacketed	1.25–1.35	Shealy—"Heat"
Air engines	1.3 –1.35	Shealy—"Heat"
Air compressors, average value	1.3	Marks—"Mechanical Engineers' H. B."
Gas engines, compression stroke	1.25–1.35	Marks—"Mechanical Engineers' H. B."
Gas engines, expansion stroke (generally)	1.30–1.50	Marks—"Mechanical Engineers' H. B."
Gas engines, expansion stroke sometimes	1.70	Marks—"Mechanical Engineers' H. B."

275. The Pressure-volume-temperature Relations For A Perfect Gas During Adiabatic Or Polytropic Processes may be found by the following formulas together with those of Sec. 249. As the derivation of the following formulas involves the calculus, the derivations will not be here given. See notes under Secs. 272 and 273 for occurrences of adiabatic and polytropic expansions in practice. The formulas are:

(232) $$PV^n = K \qquad \text{(constant)}$$

(233) $$P_1V_1{}^n = P_2V_2{}^n$$

(234) $$P_2 = P_1\left(\frac{V_1}{V_2}\right)^n$$

(235) $$V_2 = V_1\left(\frac{P_1}{P_2}\right)^{\frac{1}{n}}$$

(236) $$T_2 = T_1\left(\frac{P_2}{P_1}\right)^{\frac{n-1}{n}}$$

(237) $$T_2 = T_1\left(\frac{V_1}{V_2}\right)^{n-1}$$

(238) $$P_2 = P_1\left(\frac{\mathbf{T}_2}{\mathbf{T}_1}\right)^{\frac{n}{n-1}}$$

(239) $$V_2 = V_1\left(\frac{\mathbf{T}_1}{\mathbf{T}_2}\right)^{\frac{1}{n-1}}$$

Wherein: P and V = respectively, the absolute pressure and volume of the gas at any point along the path, in any units. K = a constant. n = the polytropic exponent which is defined by For. (221); for adiabatic processes $n = \mathbf{k} = \mathbf{C}_P/\mathbf{C}_V$. P_1 and P_2 = respectively, the absolute pressure at a first and second instant during the condition change, in any units. V_1 and V_2 = respectively, the volumes of the gas at the same first and second instants during the condition change, in any units. $\mathbf{T}_1$ and $\mathbf{T}_2$ = respectively, the absolute temperatures of the gas at the same first and second instants during the condition change, in any units.

NOTE.—THE APPLICATION OF THE ABOVE FORMULAS GENERALLY INVOLVES THE USE OF LOGARITHMS.—Although Fors. (234) to (239) can frequently be solved readily by using special slide-rules, the use of logarithms is more common and will be used in the following examples. The problems should serve to explain the *method of solving problems involving fractional exponents.*

EXAMPLE.—Find the final pressure when air in an air engine is expanded adiabatically from a volume 1 cu. ft. at 115 lb. per sq. in. abs. to a final volume of 6 cu. ft. SOLUTION.—From Table 251, $\mathbf{k}$ for air = 1.40. Hence, by For. (234), the *final pressure* = $P_2 = P_1(V_1/V_2)^n = 115 \times (1 \div 6)^{1.40} = 115 \times (0.166{,}7)^{1.40}$. To find the value of $(0.166{,}7)^{1.40}$, first find the logarithm of 0.166,7. From a table of logarithms, log 0.166,7 = 9.221,9 − 10 = −0.778,1. Now multiply this value by the exponent, thus: 1.40 × −0.778,1 = − 1.089,3. Now, find the number of which this is the logarithm, thus: $\log^{-1} - 1.089{,}3 = \log^{-1} 8.910{,}7 - 10 = 0.081{,}42$. Hence, $(0.166{,}7)^{1.40} = 0.081{,}42$ and $P_2 = 115 \times 0.081{,}42 = 9.36$ *lb. per sq. in. abs.*

EXAMPLE.—In a gas engine, what will be the volume at 15 lb. per sq. in. abs. of a given quantity of gas after polytropic expansion ($n = 1.25$) from a volume of 2 cu. ft. at a pressure of 135 lb. per sq. in. abs.? SOLUTION.—By For. (235), the *final volume* = $V_2 = V_1(P_1/P_2)^{\frac{1}{n}} = 2 \times (135 \div 15)^{\frac{1}{1.25}} = 2 \times 9^{0.8}$. Now, log 9 = 0.954,2. And, 0.8 × 0.954,2 = 0.763,36 = log 6.072. Hence, $V_2 = 2 \times 6.072 = 12.144$ *cu. ft.*

5.6

Example.—If the initial temperature of the gas of the preceding example is 1,150° F., what will be its final temperature? Solution.—By For. (236), the *final temperature* $= T_2 = T_1(P_2/P_1)^{\frac{n-1}{n}} = (460 + 1{,}150) \times (15 \div 135)^{\frac{1.25-1}{1.25}} = 1{,}640 \times \frac{1}{9}^{0.20}$. Now, $\log \frac{1}{9} = 9.045{,}8 - 10 = -0.954{,}2$. And, $0.2 \times -0.954{,}2 = 0.190{,}84 = 9.809{,}16 - 10 = \log 0.644{,}4$. Hence, $T_2 = 1{,}640 \times 0.644{,}4 = 1{,}056°$ *F. abs.*, or 596° *F.*

276. Dalton's Law Of Gases (see discussion of this same subject in Sec. 306) states that *each separate gas, in a mixture of gases, responds to changes of pressure, volume, and temperature exactly as though it were entirely isolated from the other gases.* Therefore, if all of the gases in a gaseous mixture are such (which means not near their saturation temperature) that they obey, approximately, the laws of perfect gases (Sec. 226), then the mixture, as a whole, will follow, approximately, the laws of perfect gases.

Note.—If the pressure exerted by a gaseous mixture be more definitely analyzed, it will be found that each of the constituent gases therein has the same pressure that it would have if it existed alone. Therefore, the pressure of the mixture is the sum of the pressures of its constituent gases. This principle, which is sometimes called the *law of partial pressures*, is embodied in *Dalton's law.*

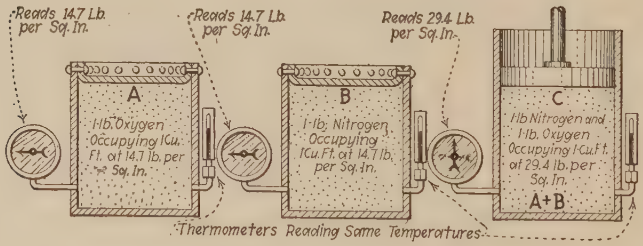

Reads 14.7 Lb. per Sq. In.
Reads 14.7 Lb. per Sq. In.
Reads 29.4 Lb. per Sq. In.
A
1-lb. Oxygen Occupying 1 Cu. Ft. at 14.7 lb. per Sq. In.
B
1-lb. Nitrogen Occupying 1 Cu. Ft. at 14.7 lb. per Sq. In.
C
1 lb Nitrogen and 1-lb. Oxygen Occupying 1 Cu. Ft. at 29.4 lb. per Sq. In.
A+B
Thermometers Reading Same Temperatures

Fig. 272.—Illustrating Dalton's law.

Example.—If (Fig. 272) 1 cu. ft. of oxygen and 1 cu. ft. of nitrogen, at atmospheric pressure, were placed together in a vessel of 1 cu. ft. capacity, then the pressure of the mixture would, since *atmospheric pressure* = 14.7 *lb. per sq. in.*, be 14.7 × 2 = 29.4 *lb. per sq. in.*

QUESTIONS ON DIVISION 8

1. What is the practical importance of the heat phenomena of gases?

2. Define a *gas*. What is the distinction between a gas and a vapor?

3. What is a *perfect* gas? Has any perfect gas been found? Name some gases which behave nearly like a perfect gas.

4. What is meant by the *condition* of a gas? By what is it determined? What is a *condition change?*

5. What is meant by saying that a certain property of a gas is maintained constant, when working with the gas laws?

6. State Boyle's law. How was it discovered? For what kind of changes does it hold?

7. To what kind of problems may Boyle's law be applied?

8. Write Boyle's law as a formula expressing it in at least three different ways. What precautions must be taken with regard to the units?

9. If a given weight of a certain gas undergoes condition changes at constant temperature, what relation always holds between its pressure and volume?

10. For constant-volume changes, how does the pressure of a gas at any temperature compare with its pressure at 32° F.? State this as a formula.

11. For constant-pressure changes, how does the volume at any temperature compare with its volume at 32° F.? Does it matter what the pressure is during such a change? State the relationship as a formula.

12. According to the formulas for constant-volume and constant-pressure changes, what would be the pressure and volume of a perfect gas at $-460°$ F.? What is this temperature called? State the conversion formulas for temperatures.

13. Give the verbal statement of Charles' law. For what kind of condition changes does it hold? Interpret the law.

14. To what kind of problems may Charles' law be applied? Does a heat exchange always accompany such changes?

15. Write Charles' law as a formula and express the formula in three different ways. What precautions must be taken as to the units in these formulas. Show that these formulas are the same as those given in answer to Question 10.

16. Give the verbal statement of Gay-Lussac's law. For what kind of condition changes does it hold? Cite simple examples to interpret the law.

17. To what kind of problems may Gay-Lussac's law be applied? Does a heat exchange always accompany such changes?

18. Write three expressions (as formulas) for Gay-Lussac's law. State the precautions which must be observed with regard to the units in which the quantities are measured.

19. Show how two of the three fundamental gas laws may be used to solve problems involving the simultaneous change of the volume, pressure, and temperature of a gas. For a given example how are the two laws selected?

20. State the formulas for the combined gas law. Show their derivation.

21. What is the constant relationship between the pressure, volume, and temperature of a given weight of a perfect gas as the gas undergoes condition changes? Express it by a formula.

22. In what units may the values of the gas properties (pressure, volume, and temperature) be expressed when they are used with the values of the gas constant as tabulated in this division? How are the gas-constant values determined?

23. Give a verbal statement of the general gas law. Why is it considered important? What is it based on?

24. Write the general-gas-law formula and the formulas which result from it. Show the derivation of the formula.

25. What two types of problems are, in general, solvable by the general gas law?

26. What is the engineering definition of density? What unit is widely used for measuring densities? State the formulas which show the interrelations between volume, weight, and density.

27. Is the density of gases a constant or variable quantity? Explain fully.

28. Write the equations which show the relation between the density of a gas and other properties of the gas.

29. Explain fully how air drafts may be caused by differences in density.

30. Wherein do the heat effects on gases differ from those on solids and liquids? Explain fully.

31. How much disgregation work is done when a perfect gas is heated? How was this determined? Make a sketch and explain the experiment.

32. What two effects may be produced when heat is added to a gas? Explain experiments, using sketches, to prove that these two effects are produced.

33. Explain fully how it is that a gas does external work when it expands. Draw a sketch to show how a gas does external work.

34. What is a *throttling expansion?* Explain what happens in such an expansion.

35. Explain fully, using sketches, how an area may be used to represent the work done by a constant force. A variable force. Does each area unit necessarily represent one force unit? Why?

36. What is the significance of the area under a pressure-volume graph? Explain fully, using sketches.

37. What is meant by *effective work? Total work?* What is the difference between these two called?

38. Is the specific heat of a gas a fairly well defined quantity like that of a solid or liquid? Why? Explain.

39. Explain the significance of the specific heat of a gas at constant volume. Draw a sketch to illustrate.

40. Is the specific heat of a gas at constant pressure greater or less than that at constant volume? Why? Does its value depend upon the pressure? How would you prove this?

41. May a gas have other specific heats than those just referred to? When?

42. Explain the significance of an infinite specific heat. A specific heat of zero. A negative specific heat.

43. Of what importance are the energy relations which accompany condition changes of gases? Why should condition changes not be spoken of as expansions and compressions?

44. How many different kinds of condition changes are there for gases? Of what definite kind are gas cycles composed?

45. Do the laws and formulas, of this division apply to expansions through orifices or nozzles? Why?

46. State the energy relations for a constant-volume change. How much external work is done? What becomes of the added heat?

47. Write the energy-relation formulas for a constant-pressure change. Why must more heat be added for a given weight of gas and a given temperature increase than for a constant-volume change? Derive the formulas.

48. Write the energy relations for a constant-temperature change. What is such a change called? How are these relations derived?

49. What name is given to a condition change which involves no heat transfer? Is any external work done during such a change? Draw a sketch to show an ideal apparatus with which such a change might be effected.

50. Write and derive the energy relations for an adiabatic change.

51. What property of a gas remains constant during a polytropic change?

52. Write and derive the energy relations for a polytropic change.

53. State the pressure-volume relations for a perfect gas undergoing a polytropic change and explain the meanings of the symbols in the formula.

54. Explain the use of logarithms for solving equations involving fractional exponents.

PROBLEMS ON DIVISION 8

1. At 32° F. and atmospheric pressure (14.7 lb per sq. in. abs.) 1 lb. of air occupies 12.39 cu. ft. At the same temperature what pressure will it exert when confined in 2 cu. ft.?

2. Three cubic feet of air at atmospheric pressure are to be compressed at constant temperature to 100 lb. per sq. in. gage. What volume will the air then occupy?

3. If a given weight of gas at 32° F. exerts a pressure of 60 lb. per sq. in. abs., what pressure will it exert at 100° F. when in the same volume? Solve by For. (115).

4. Using For. (117) and the data of Prob. 1, find the volume of 1 lb. of air at atmospheric pressure and 70° F.

5. Using For. (121) and the data of Prob. 1 find the pressure exerted by 1 lb. of air when confined in 12.39 cu. ft. at 300 ° F.

6. A tank holds a certain volume of gas at 70° F. and 60 lb. per sq. in. gage pressure. To what temperature must the gas be heated so that the pressure shall be 100 lb. per sq. in. gage?

7. A given weight of gas at atmospheric pressure and 40° F. occupies 3 cu. ft. What volume will the same gas occupy at atmospheric pressure and 1,800° F.?

8. At what temperature will 1 lb. of air at atmospheric pressure occupy 15 cu. ft.? (Use data of Prob. 1.)

9. A certain gas occupies 10 cu. ft. when at 50° F. and under a pressure of 1 atmosphere. By using two of the fundamental-law formulas, find the volume of the same gas at 80° F. and a pressure of 2.5 atmospheres.

10. Find the pressure exerted by the gas by Prob. 9 when the volume is 8 cu. ft. and the temperature is 100° F. (Use two steps.)

11. What temperature would the gas of Prob. 9 have when its volume is 5 cu. ft. and its pressure is 30 lb. per sq. in. abs.? (Solve in two steps.)

12. Solve Prob. 9 in one step.

13. A quantity of gas at 60° F. and atmospheric pressure has a volume of 7 cu. ft. What pressure will the same gas exert when at 200° F. and in a volume of 6 cu. ft.? (Solve in one step.)

14. At what temperature will the pressure and volume of the gas of Prob. 13 be 30 lb. per sq. in abs. and 5 cu. ft. respectively?

15. A receiver of 15-cu. ft. capacity contains 9 lb. of acetylene. At what temperature will the pressure in the tank become 200 lb. per sq. in. gage?

16. What must be the capacity of a receiver to hold 50 lb. of air at a pressure of 250 lb. per sq. in. gage and at a temperature of 210° F.?

17. When 9 lb. of a certain gas occupy 5 cu. ft., the pressure and temperature are, respectively, 175 lb. per sq. in. gage and 290° F. Which is the value of the gas constant?

18 A tank of 10-cu. ft. capacity contains air at atmospheric pressure and 70° F. Air is forced into this tank until the pressure rises to 200 lb. per sq. in. gage, and the temperature to 75° F. What weight of air has been forced into the tank?

19. If 30.6 lb. of oxygen is confined in a 3-cu. ft. container, what is the density of the gas?

20. If, under certain conditions, the density of air is 0.08 lb. per cu. ft., how much will 88 cu. ft. of the air weigh?

21. What is the density of nitrogen at 100 lb. per sq. in. gage and 80° F.?

22. From the result of Prob. 21 find the density of nitrogen at 80° F. and atmospheric pressure.

23. From the result of Prob. 21 find the density of nitrogen at 1800 lb. per sq. in. gage and 200° F.

24. How many foot-pounds are represented by the shaded area of Fig. 273?

25. A tank held 40 cu. ft. of air at 200 lb. per sq. in. gage. This air is cooled in the tank to 70° F. and its pressure is now 150 lb. per sq. in. gage. How much heat has been extracted and how much vibration work is done on the air?

26. If 6 lb. of air are heated at constant pressure from 60° F. to 150° F., how much heat is added, and how much external and vibration work is done?

27. A compressor delivers 100 cu. ft. of air per min. at a pressure of 100 lb. per sq. in. gage and at 130° F. If this air is cooled, at constant pressure, so that only 90 cu. ft. are delivered at another point, how much heat is abstracted each minute? How much external and vibration work is done during the cooling?

28. It is desired to compress 3 cu. ft. of air at atmospheric pressure to 100 lb. per sq.

in. gage. How much heat must be withdrawn to accomplish this without changing the temperature and where does this heat come from?

29. Compute the work done by 1 lb. of air in expanding from 175 lb. per sq. in. gage to 15 lb. per sq. in. gage at a constant temperature of 100° F.

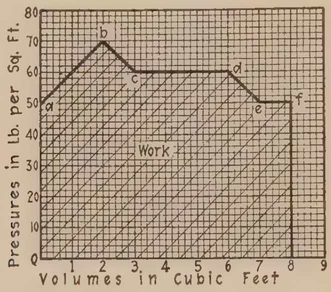


Fig. 273.—Pressure-volume work diagram.

30. During an adiabatic process the temperature of 20 lb. of air changed from 80° to 150° F. How much external work was done on the gas?

31. One pound of air expands adiabatically from 300 lb. per sq. in. abs. and 200° F. to 15 lb. per sq. in. abs. What are its initial volume, final volume, and final temperature?

32. In Prob. 31, how much external work is done by the expanding air and how much vibration work?

33. In an air compressor, 10 cu. ft. of air at 100° F. and under a pressure of 14 lb. per sq. in. abs. are compressed adiabatically. The final pressure is 60 lb per sq. in. abs. Compute the volume and temperature of this air after compression.

34. If, during a polytropic process for which $n = 1.2$, the temperature of 20 lb. of air changed from 80° to 150° F., how much external work was done by the gas? How much heat had to be added?

35. During the compression of an ideal gas 40,000 ft.-lb. of work are expended and 8 B.t.u. are taken from the gas by conduction. How much vibration work is done on the gas?

36. During a compression following the law $PV^{1.3}$ = a constant, the temperature of the air rises from 80° to 200° F. How much heat has been transferred to the cylinder walls per pound of air?

37. If 1 lb. of nitrogen expands polytropically ($n = 1.35$) from 100 lb. per sq. in. gage and 120° F. to atmospheric pressure, what will be the final volume and temperature?

38. Compute the heat added, external work, and vibration work in Prob. 37.

39. If oxygen were expanded adiabatically from an initial condition of 1,800 lb. per sq. in. abs., 2 cu. ft., and 90° F. until its temperature reached −280° F., what would be its final pressure and volume?

DIVISION

MELTING AND FREEZING OF SUBSTANCES

277. Melting Or Fusion is the process by which a substance is changed (Sec. 103) from the solid to the liquid state by added heat.

NOTE.—THE TEMPERATURE AT WHICH A SUBSTANCE MELTS OR FUSES is called its *temperature of fusion*, or simply its *melting point*, see Table 285 for values.

NOTE.—BEFORE PROCEEDING THE READER SHOULD REVIEW carefully the material in Div. 4, starting with Sec. 96, which discusses the three ways in which heat which is added to a substance may be expended, and the three different kinds of work which heat added to or abstracted from a substance may do.

278. Solidifying Or Freezing is the process by which a substance changes (Sec. 161) from the liquid to the solid state; freezing is always accompanied or occasioned by the abstraction of heat from the substance.

NOTE.—THE TEMPERATURE AT WHICH A SUBSTANCE SOLIDIFIES or freezes is called its *temperature of solidification*, or simply its *freezing point*. The usual freezing point (temperature) for any substance is the same as the melting point (Sec. 277) of that substance.

279. All Crystalline Substances Have Definite Temperatures Of Fusion And Solidification.—That is, every substance, as *mercury*, *ice*, *sulphur*, *silver*, in which the molecules are grouped in the form of crystals of a definite uniform structure, has a certain fixed, characteristic temperature, corresponding to a given pressure, at which both melting and solidification occur.

NOTE.—WHEN A CRYSTALLINE SUBSTANCE UNDER A CONSTANT PRESSURE UNDERGOES EITHER MELTING OR SOLIDIFYING, its temperature remains constant from the instant that melting or solidifying begins until the process is completed, as discussed more fully in following Sec. 289.

280. All Non-crystalline Or Amorphous Substances Have Indefinite Temperatures Of Fusion And Solidification.—That is, every substance, as *glass*, *wax*, *resin*, *glue*, in which the molecules are arranged in an indeterminate, irregular and non-uniform formation, have no definitely fixed temperature at which both melting and solidification occur.

Note.—Non-crystalline Substances Assume All Degrees Of Viscosity (Sec. 165) both in melting and in solidifying. If a glass rod is heated in the flame of a blow-torch, it will become soft and may be easily bent. If the heating is continued, the glass will become more and more plastic. Finally, it will begin to melt. But if the heat is still applied, after melting begins, the temperature of the glass will continue to rise. That is, no point is reached, as heat is applied, at which the temperature remains constant for an interval.

281. The Melting And Solidifying Temperatures Of Dissolved Or Alloyed Substances are, generally lower than the melting and solidifying temperatures of the simple substances which compose the solutions or alloys. This principle is of great practical importance in many ways. It provides a ready means (Fig. 274) for producing ice artificially. Also (Fig. 275) it, by virtue of the low melting temperatures of certain alloys, is the basic principle of many fire-extinguishing devices. By varying the proportions (Fig. 276) of the metals used in an alloy, the melting point of the alloy can, within a certain range, be made any desired temperature.

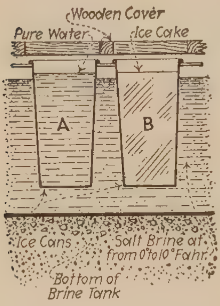


Fig. 274.—Illustrating use of salt brine in artificial ice-making. The salt brine can be cooled far below 32° F.—the freezing point of water—before it begins to freeze.

Example.—When salt is dissolved in water (Fig. 274) the freezing temperature of the brine thus formed may be many degrees lower than the freezing temperature of pure water. Hence, the pure water in the can *A* (Fig. 274) will be frozen into a solid cake of ice, as *B*, when the can is immersed in the low-temperature brine for a sufficient length of time.

Example.—A certain alloy, called *Darcet's Metal*, is composed of 2 parts bismuth, 1 part lead and 1 part tin. The melting temperature of this alloy is 203° F., which is (Table 285) many degrees lower than the melting temperature of either of the component metals.

Example.—An alloy of tin, lead, and bismuth has been used (Fig. 277) for making the fusible elements of safety plugs for steam boilers. The alloy in the cap, *F* (Fig. 277), absorbs heat from the furnace gases. But normally the conduction of this heat to the water in the boiler proceeds at a sufficiently rapid rate to prevent the temperature of the alloy from reaching the melting point.

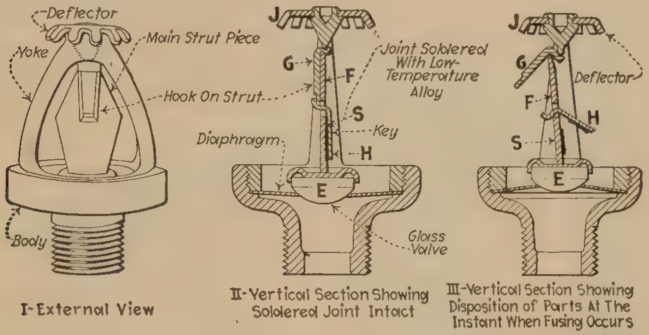

Deflector
Main Strut Piece
Yoke
Hook On Strut
Body
I-External View
J
G
F
Joint Soldered With Low-Temperature Alloy
S
Key
Diaphragm
H
E
Glass Valve
II-Vertical Section Showing Soldered Joint Intact
J
G
Deflector
F
H
S
E
III-Vertical Section Showing Disposition of Parts At The Instant When Fusing Occurs

Fig. 275.—Details of *Grinnel* sprinkler head for use in fire-protection systems.

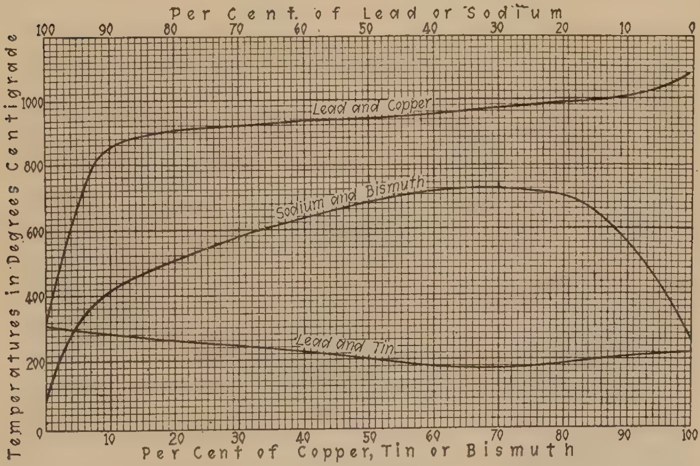


Fig. 276.—Curves showing variations of melting temperatures of alloys corresponding to variations in the proportions of the metal constituents of the alloys.

However, if the water level falls low enough to expose the cap *F* directly to the steam in the boiler, then, the steam not being able to conduct away the heat as rapidly as the heat is absorbed by the cap, the temperature of *F* quickly rises to the melting point of the alloy. Then the cap *F* melts and is blown out. The blowing out of the plug liberates the steam in the boiler and prevents a possible explosion.

282. The Use Of Metal Alloys In The Liberating Devices Of Sprinkler Or Fire Protection Systems (Fig. 275) permits the sprinklers to be adjusted for operation (Fig. 278) at exactly the highest temperature that can be allowed, with safety, in the building which the apparatus is designed to protect.

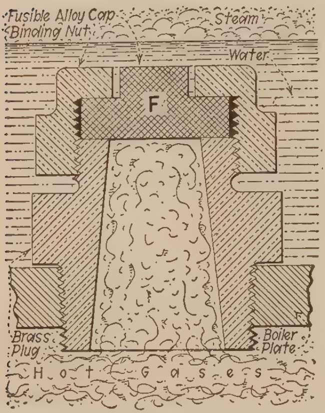


Fig. 277.—Fusible safety-plug for steam boilers.

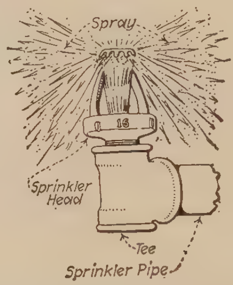


Fig. 278.—*Grinnel* sprinkler-head in action.

Explanation.—The key, *H* (Fig. 275), is soldered to the main strut-piece, *F*, by an alloy, *S*, which fuses at the desired temperature. If the normal temperature of the room in which the sprinkler is installed is 100° F. or less, the fusing temperature of the solder, *S*, is usually fixed at 155° F. If the normal room-temperature is to be between 100° and 150° F., then an alloy with a fusing temperature of 212° F. may be used. Should the air in the room become heated to the fusing temperature of the alloy, the soldered joint, *S*, will be melted out. The key, *H*, and hook, *G*, will thus become disjointed. The glass valve, *E*, being released from the restraint of the strut-piece, *F*, will then be blown out by the pressure of the water beneath. The issuing water (Fig. 278) will be broken into spray by the deflector, *J*, and will, presumably, extinguish the fire.

283. The Utility Of Fusion Pyrometers For Measuring High Temperatures (Fig. 279) depends upon the facility with which the melting temperatures of alloys or compositions of substances can be adjusted to desired degrees of heat intensity. Such pyrometers are commonly used for determining the temperatures of pottery furnaces. They consist of a graduated series of two or more clay pyramids, or *Seger cones*. The pyramids are about 2.5 in. high. They are composed of several different varieties of clay, which are mixed in such proportions as to give a different melting point to each pyramid in the series. The difference between consecutive melting points is about 35° F. A range of temperature from about 600° to 3,400° F. may thus be covered. The cones are stamped with numbers. A definite melting temperature corresponds to each number in the series.

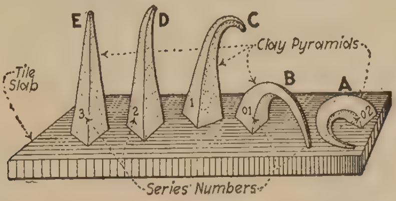


FIG. 279.—A fusion pyrometer—melting temperatures in degrees Fahrenheit are as follows: A = 2,000. B = 2,035. C = 2,070. D = 2,105. E = 2,140.

EXPLANATION.—When a series of Seger cones, or clay pyramids, is placed in a furnace which is being fired up for service, the cone or pyramid which has the lowest melting point will be the first to lose its upright form. The temperature corresponding to the series-number on a cone or pyramid is reached when the tip of the cone or pyramid has bent over *B* (Fig. 279) so that it just touches the tile surface on which the cone or pyramid stands.

NOTE.—FUSION PYROMETERS GIVE ONLY APPROXIMATE TEMPERATURE MEASUREMENTS—but these are sufficiently accurate for the purposes for which the cones are properly employed.

284. Temperature Pendants (Fig. 280), for giving approximate indications of flue-gas temperatures in boiler plants, are made by adjusting the proportions of the alloy of which the pendants are cast to give a graded series of melting points. The utility of these devices as they are ordinarily furnished is limited to a range of temperature between 425° and 550° F. There is a 75° difference between the fusing points of the three pendants. They are usually applied by suspending the three pendants in the path of the gases.

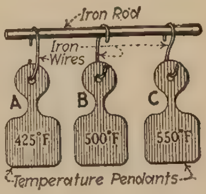


FIG. 280.—Green's temperature pendants—melting temperature stamped on eaco pendant.

EXAMPLE.—Suppose the pendants *A*, *B*, *C* (Fig. 280) to be suspended in a boiler breeching. If pendant *A* melts while the others remain intact, then the temperature lies between 425 and 500° F. If pendants *A* and *B* both melt while pendant *C* remains intact, then the temperature lies between 500 and 550° F.

285. Table Showing The Melting And Freezing Points (Temperatures) Of Various Substances under atmospheric pressure. Values are from the following authorities: S = Smithsonian Tables. M = Marks' Mechanical Engineers' Handbook.

Substance	Melting and freezing point, deg. Fahr.	Authority	Substance	Melting and freezing point, deg. Fahr.	Authority
Alcohol	−143	S	Lead	621	S
Aluminum	1,218	S	Magnesium	1,204	S
Antimony	1,166	S	Magnesium chloride	1,306	S
Barium	1,562	S	Magnesium sulphate	302	S
Bismuth	520	S	Mercury	−38	S
Borax	1,366	S	Nickel	2,646	S
Calcium	1,490	S	Oxygen	−360	S
Calcium chloride	1,404	S	Platinum	3,191	S
Carbon[1]—above	6,300	S	Silver	1,761	S
Carbon dioxide[1]	−70.6	S	Sodium	208	S
Carbon disulphide	−166	S	Sulphur[2]	224 235 247	S
Copper	1,981	S	Tantalum	5,252	S
Glycerine	4	M	Tin	449	S
Gold	1,945	S	Tungsten	6,152	S
Hydrogen	−434	S	Turpentine	14	M
Iodine	236	S	Ice (water)	32	
Iron (pure)	2,786	S	Zinc	787	S

[1] Sublimes (Sec. 163).

[2] Sulphur occurs in three solid forms having the values as shown.

286. Many Substances May Be Changed From The Solid To The Liquid State By Solution.—That is, by mixing them with other substances which are already in the liquid state, as when salt or sugar is dissolved (Sec. 170) in water, or when shellac is dissolved in alcohol. In the dissolution of a solid substance by this process, energy is expended in causing the molecules of the *solute*, or solid substance, to separate from one another and intermingle intimately with the molecules of the *solvent*, or liquid substance. When some solutes are dissolved, even their molecules (or some of them) are broken up into *ions*.

287. The Heat In The Substances, Or In Surrounding Substances, Supplies This Energy.—A portion of the vibration or sensible heat (Sec. 54) of the mixture is (by doing disgregation work) transformed into potential energy due to the mutual rearrangement of the molecules. Therefore, in all mechanical solutions—that is, solutions which occur without violent chemical reactions between the solute and the solvent—heat energy must be absorbed while the process of dissolution is proceeding. The production of *freezing mixtures* depends upon this principle. Such mixtures may be made by mixing certain solid substances, as sodium chloride (common salt) or calcium chloride, with snow or broken ice.

EXPLANATION.—If a quantity of snow or broken ice is placed in a vessel (Fig. 281) and is mixed therein with common salt, the snow or ice will melt quickly. The disgregation heat which the snow or ice must absorb (Sec. 98), in order that melting may occur, is given up by the surrounding objects. If more salt is present than can go into a saturated solution of salt and water, the temperature of the salt-ice mixture will tend to become that at which a saturated solution of salt freezes (−6° F.). The temperature will attain this value if heat does not reach the ice water faster than the ice can melt. If less salt is present than that which is necessary to produce the saturated solution, the temperature of the brine-ice mixture will be higher than −6° F. In all cases, the temperature (Fig. 282) will depend mainly upon the quantity of the dissolved salt. The greater the proportion of salt to water in the brine, the lower the melting temperature of the ice in the brine. If a vessel (Fig. 281) containing a liquid that freezes at about the freezing point of water be submerged in the freezing mixture, the

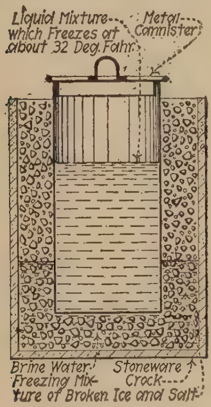

Liquid Mixture which Freezes at about 32 Deg. Fahr.
Metal Cannister
Brine Water
Freezing Mixture of Broken Ice and Salt
Stoneware Crock

FIG. 281.—Illustrating application of freezing mixture.

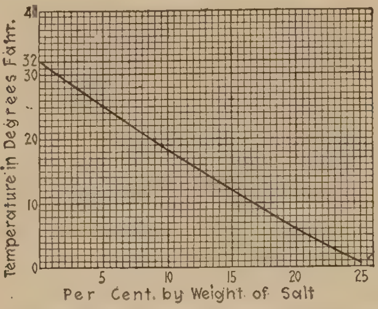


FIG. 282.—The freezing temperature of brine varies with the percentage of dissolved salt.

liquid will be quickly frozen. This is the operating principle of the ordinary household *ice-cream freezer.*

Note.—A Freezing Mixture is one which may be used to produce low temperatures. A mixture containing about 3 parts of snow and 1 part of common salt will produce a temperature of from 4° to 6° below 0° F. A mixture containing 3 parts of calcium chloride and 2 parts of snow will produce a temperature of 50° below 0° F. The mixing of equal parts of nitrate of ammonia and water may result in reducing the temperature of the mixture through 46° F.

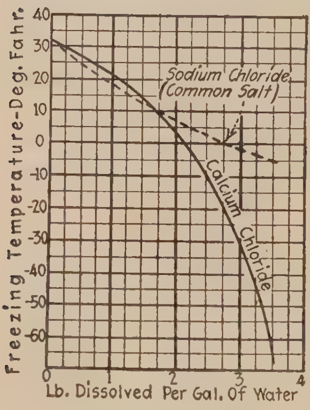


Fig. 283.—Graphs showing freezing temperatures of calcium-chloride and sodium-chloride (common salt) solutions, in water, of different concentrations.

Note.—Water For Extinguishing Fires may, when kept in barrels which are exposed to freezing weather temperatures, be kept fluid by dissolving (see Fig. 283) a quantity of calcium chloride therein. Calcium chloride is preferable, for this purpose, to common salt. The corrosive action of common salt on metals is considerable. Also, the salt tends to creep from the solution, by capillary action, and crystallize on the outside of the containing vessel. If calcium chloride is not obtainable, common salt may be used.

288. The Effect Of Pressure Upon The Melting And Freezing Temperature Of Substances will now be considered. If a body of water has imposed on it a pressure many times greater than the pressure of the atmosphere, it will continue in the liquid state even though its temperature be reduced somewhat below its freezing point (Sec. 278) under atmospheric pressure. But if a mass of lead is melted under atmospheric pressure and is then subjected to a pressure greatly in excess of atmospheric, it will again become solid at a higher temperature than the temperature under which it was melted. These phenomena suggest the following principles: (1) *The temperatures of melting and solidification of any substance which expands while solidifying and contacts while melting is lowered by applying pressure.* (2) *The temperature of melting and solidification of any substance which contracts while solidifying and expands while melting is raised by applying pressure.*

EXAMPLE.—A small wire (Fig. 284) with weighted ends, WW, is slung over a rectangular block of ice. The temperature of the surrounding air remains constantly at 32° F. The pressure, due to the suspended weights, WW, which the wire exerts, upon the narrow area upon which it rests, reduces the freezing temperature of that area slightly below 32° F. Hence, the ice under and in immediate contact with the wire begins to melt. Presently, the wire will have cut into the ice-block to a considerable depth. But as the wire descends it will displace the water which results from the melting. The water will gather above the wire. Being relieved from the pressure of the wire, the water will again freeze to ice. The fissure which the wire forms as it descends is thus being constantly closed above the wire. Hence the wire becomes embedded in the ice-block as it cuts its way through. The process of melting under pressure and freezing again when the pressure is relieved is called *Regelation.*

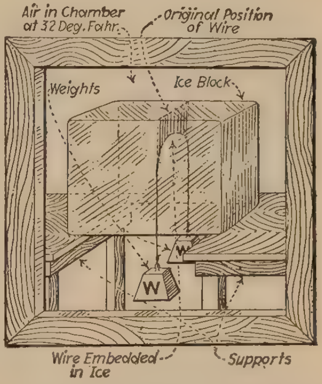


FIG. 284.—Regelation—illustrating effect of pressure on the melting temperature of ice.

NOTE.—THE FREEZING TEMPERATURE OF A BODY OF WATER MAY BE LOWERED from 32° to about 31.9865° F. by adding 14.7 lb. per sq. in. (1 atmosphere) to the normal atmospheric pressure on its surface, and the freezing temperature will decrease approximately 0.013,5° F. for each additional atmosphere of pressure added.

289. Latent Heat Of Melting Or Fusion will now be considered. As defined and explained in Sec. 106: "Latent heat is the heat energy which is required to produce changes in the physical state (Sec. 49) of a substance." It has been found by thousands of experiments that, for each substance, a certain definite amount of heat is required to convert, into the liquid state, 1 lb. of the solid substance which is already at its melting temperature. Following Table 291 shows values. This amount of heat which is required to convert 1 lb. of a substance, which is in the solid state and at its melting temperature into the liquid state, at the same temperature, is called the latent heat of melting for the substance. See also Sec. 103.

EXPLANATION.—If a quantity of cracked ice (Fig. 285) be melted over the flame of a spirit lamp, the mercury in the Fahrenheit thermometer will stand at the 32° mark until the ice is entirely changed to water. But the instant the last vestage of the original mass of ice has disappeared, the mercury will begin to rise. Although the thermometer indicates no rise of temperature while the melting is in progress, the ice is, nevertheless, constantly absorbing heat from the flame. But this heat is wholly expended as disgregation work—in overcoming the cohesion among the molecules of the ice crystals (Sec. 50) and in separating them. That is, the energy of this latent or unindicated heat is used up in the work of disintegrating the compact molecular structure that exists in ice and in giving the molecules that freedom under which they exist in water.

Hence, the "latent" heat which is not revealed by the thermometer resides within the water in the form of molecular potential energy, or as the additional energy of position which the molecules possess by virtue of their increased distance from one another. This phenomenon is, presumably, present in the melting of all substances.

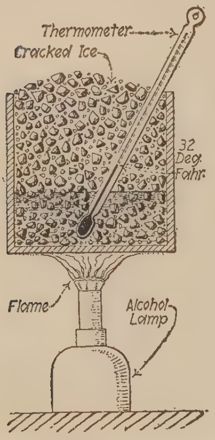


FIG. 285.—Illustrating latent heat.

290. Similarly, When A Substance Changes From The Liquid To The Solid State, The Latent Heat Energy Existing Within The Liquid Is Given Up to surrounding substances. Or, stating the same idea in a different way: As a substance is changed from the liquid to the solid state, the latent heat energy (disgregation heat) which resides within the liquid must, to effect the change, be abstracted from the liquid. Hence (Fig. 286) the temperature of any substance which has a determinate freezing point (Sec. 278) continues constant while the substance is changing from the liquid to the solid state.

EXAMPLE.—A crucible containing molten zinc (Fig. 286) at a temperature of 896° F. is permitted to cool. The liquid zinc begins giving up its sensible, or vibration heat (Sec. 97). Therefore, the temperature falls gradually, *AB*, until 787° F., which (Table 285) is the temperature of solidification, is reached. The temperature remains at 787° (*BC*, Fig. 286) until the zinc has completely solidified. During this *BC* interval the zinc is giving up its latent heat of melting, or disgregation heat. When all of this heat has been abstracted, the solid zinc then again begins giving up its sensible or vibration heat. Hence, the gradual fall of temperature is resumed as shown at *CD*.

NOTE.—It Is Probably True That The Melting Of Every Crystalline Substance Requires The Expenditure Of A Certain Quantity Of Heat, depending upon the nature of the substance, to change the molecular arrangement which exists in the solid state of the substance to that which exists in the liquid state. This, however, cannot be asserted without qualification, since the melting temperatures of some substances are so extremely high that accurate observations of the phenomena involved cannot be made.

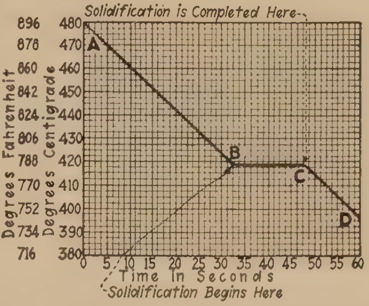


FIG. 286.—Graph showing temperature conditions during the cooling and solidification of a mass of molten zinc.

NOTE.—The Early Investigators Of Heat Phenomena Gave The Name Latent Heat to the heat energy (disgregation heat) which is expanded in reconstructing the molecular arrangements of melting substances. It was presumed that this energy simply soaked into a melting substance and remained concealed therein in a deadened or dormant condition.

NOTE.—Dr. Black, A Scotch Physicist, In 1760 Determined The Latent Heat Of Ice.—He placed two vessels, one containing 1 lb. of ice, and the other containing 1 lb. of water at 32° F., in a chamber in which the temperature was kept constant at about 47.3° F. The temperature of the 1 lb. of water rose to 39.2° in 0.5 hr. The melting of the 1 lb. of ice and the heating of the resulting water to 39.2° consumed 10.5 hr.

The experimenter assumed that during each ½ hr. equal quantities of heat passed from the surrounding air into the 1 lb. of ice and the 1 lb. of water. That is, (so Black computed) the ice received $39.2 - 32 = 7.2$ *B.t.u. per* 0.5 *hr.* Hence, in 10.5 hr. the ice absorbed $(10.5 \div 0.5) \times 7.2 = 151.2$ *B.t.u.* Only 7.2 B.t.u. were required to raise the temperature of the melted ice to the temperature of the chamber. Therefore, a *quantity of heat* $= 151.2 - 7.2 = 144$ *B.t.u.*—the latent heat of ice—was presumed by Dr. Black to have been absorbed and stored in the water in a "latent" or dormant condition.

Dr. Black's method was not strictly accurate because, actually, heat transfer is, as explained in Div. 5 dependent not only on the time during which the heat flows but also on the average difference between the temperature of the cold body and that of the hot body—the thermal pressure. Now, the average thermal pressure forcing heat into the 1 lb. of water was, actually, slightly different from that which forced heat into the 1 lb. of ice. Hence, Dr. Black's result was inaccurate, because he assumed that both of these thermal pressures were the same. A more accurate method of determining the latent heat of melting is the method of mixtures (similar to that of Sec. 94). It is remarkable how nearly correct Dr. Black's result actually was.

Later and more consistent determinations have shown that the latent heat of melting of ice is more accurately 143.3 B.t.u. per lb. However, the value of 144 B.t.u. per lb. is the one which is commonly used in engineering work.

291. Table Showing Latent Heats Of Melting Or Fusion Of Different Substances.—The values shown here have been computed from the SMITHSONIAN TABLES.

Substance	Latent heat of melting, in B.t.u. per pound
Aluminum	138.2
Bismuth	22.75
Copper	75.6
Iron, gray cast	41.4
Iron, white cast	59.4
Iron slag	90.0
Iodine	21.08
Ice	143.33
Lead	9.65
Mercury	5.08
Nickel	8.35
Platinum	49 0
Silver	37.9
Sulphur	16.87
Tin	25.2
Zinc	50.63

NOTE.—STRICTLY, THE LATENT HEAT OF MELTING OF A SUBSTANCE WILL VARY WITH THE PRESSURE WHICH IS IMPOSED ON THE SUBSTANCE WHILE IT IS MELTING, if the substance expands or contracts due to the melting. This is because that if the substance changes volume in melting external-work heat will (unless the melting occurs in a vacuum) have to be supplied—in addition to the disgregation heat—to do the external work which is occasioned by any change of volume. However, as explained in Sec. 103, the amount of this external work is so small in practical cases that it may be safely neglected.

292. The Heat Required For Melting A Given Weight Of A Substance together with that required to warm the substance to its melting point, may be computed by the following formula:

$$Q = W[C(T_M - T) + L_M] \qquad \text{(B.t.u.)} \tag{240}$$

Wherein: Q = heat, in British thermal units, required for warming and melting the substance. W = weight of substance, in pounds. T_M = temperature, in degrees Fahrenheit, at which the substance melts. T = initial temperature, in degrees Fahrenheit. C = mean specific heat of the substance, between T and T_M, see Table 90. L_M = latent heat of melting, in British thermal units per pound, see Table 291.

Example.—A block of ice weighs 201.5 lb. Its temperature is 29° F. How much heat will be required to melt it? Solution.—By Table (90), the *specific heat of ice* = 0.504 *B.t.u. per lb.* By Table (291) the *latent heat of melting of ice* = 143.33 *B.t.u. per lb.* Hence, by For. (240), the *required heat* = $Q = W[C(T_M - T) + L_M] = 201.5 \times \{[0.504 \times (32 - 29)] + 143.33\} = 29{,}186$ *B.t.u.*

Example.—A copper ingot weighs 55 lb. Its temperature is 80° F. How much heat will be required to melt it? Solution.—By Table (90) the *specific heat of copper* = 0.093 *B.t.u. per lb.* By Tables 291 and 285, the latent heat of melting and the melting temperature of copper are, respectively, 75.6 *B.t.u. per lb.* and 1981° F. Hence, *the required heat* = $\{[(1981 - 80) \times 0.093] + 75.6\} \times 55 = 13{,}882$ *B.t.u.*

QUESTIONS ON DIVISION 9

1. What chiefly distinguishes the molecular structure of a substance in the solid state from the molecular structure of the same substance in the liquid state?
2. What is meant by *temperature of fusion?* *Temperature of solidification?*
3. What characteristic of substances apparently determines whether the melting temperature of a substance shall be constant or variable?
4. The freezing temperature of a mixture of sugar and water is lower than the freezing point of pure water. Why is this?
5. What are *freezing mixtures?* How may they be utilized practically?
6. What, in general, is the effect in the melting points of two or more different metals when an alloy is formed with the metals? In what respect is this principle of practical utility? Give an example.
7. In what manner, other than by melting, can some solid substances be reduced to a liquid state?
8. What is a *solute?* A *solvent?*
9. In what ways do variations of pressure affect the melting and freezing temperatures of substances?
10. What is meant by *latent heat of fusion?*
11. What becomes of the latent heat in a liquid substance while the substance is solidifying?
12. Describe and give values for Dr. Black's latent-heat experiment.

13. Does the latent heat of fusion perform a constant action function in a liquid substance, that is does it do work—or does it exist in a state of dormancy? In any event, what is the function of latent heat of fusion?

14. Why did the early experimenters use the term "latent" in defining the non-sensible heat that goes into melting substances?

15. What is a *fusion pyrometer?*

16. Explain the use of Seger cones.

17. What are *temperature pendants?*

PROBLEMS ON DIVISION 9

1. How much heat is required to change 300 lb. of ice at 22° F. to water at 32° F.?

2. An ice-can (Fig. 274) contains 258.3 lb. of water at 65° F. How much heat will pass from the water in the can to the brine in the tank while the water is freezing to a solid block of ice at 32° F.?

3. What is the approximate freezing temperature of a mass of pure water if the gage pressure on its surface is 110 lb. per sq. in.?

4. A ton of tin at a temperature of 80° F. is heated and melted in a crucible to 660° F. How much heat is absorbed by the tin?

DIVISION 10

VAPORIZATION

293. Vaporization is the change in state (Sec. 49) of a substance which occurs when the substance is transformed from the liquid state into the vapor form of the gaseous state. See Sec. 225 for the distinction between a vapor and a gas. Vaporization is a common phenomena and one of great practical importance.

EXAMPLES.—In the steam power plant (Div. 15) it is vaporization that changes the boiler water into steam when the water is heated. In the refrigerating plant (Div. 18) it is the vaporization of the liquefied ammonia or other liquefied gas which indirectly produces the artificial ice and the low temperatures which are necessary in cold-storage houses. It is due almost wholly to vaporization that cooling towers and spray ponds (see the author's STEAM POWER PLANT AUXILLIARIES AND ACCESSORIES) cool the circulating water. In the home, it is vaporization which drys the family "wash."

NOTE.—STEAM IS MERELY WATER VAPOR or, as it is sometimes called, *aqueous vapor.* Hence, as will be explained in Div. 11, much valuable information concerning the properties of water vapor may be obtained from steam tables, an example of which is given in Table 394.

294. There Are Two Kinds Of Vaporization: (1) Evaporation. (2) Ebullition. *Evaporation* (Fig. 155-*I*) *is vaporization which occurs only at the free surface of a liquid.* Evaporation takes place only below the boiling point of a liquid. *Ebullition* (Fig. 155-*II*) *or boiling is vaporization which takes place from within the body of a liquid,* the evolved vapor passing through the liquid to the surface. Each of these two forms of vaporization is discussed in succeeding sections.

NOTE.—SUBLIMINATION (Fig. 155-*III*) is sometimes considered as a form of evaporation. But in this book it is deemed best to treat it as a distinct phenomenon. It is discussed in Sec. 163.

295. Evaporation is occurring about us continually. Water—or any liquid—left in an open vessel gradually disappears. But some liquids evaporate more rapidly than others. Thus, alcohol evaporates more rapidly than water; ether evaporates more rapidly than alcohol. In each of these cases the liquid which evaporates is transformed into a vapor and passes away as such.

Note.—A "Volatile" Substance is one which will evaporate freely at a relatively low temperature. The term "volatile," however, is generally used only in comparing two or more substances. One substance is said to be more volatile than a second if, at a given temperature, the first substance tends to evaporate more freely than the second. Thus, alcohol is more volatile than water and less volatile than ether. Of two substances, the more volatile will, for a given pressure, have the lower boiling point (Sec. 315) and will, for a given temperature, have the greater vapor pressure (Sec. 304).

296. Evaporation Of Liquids Occurs At All Temperatures provided the space which is in contact with the liquid does not contain a saturated (Sec. 305) vapor of the liquid. Many examples of this fact are matters of common observation.

Example.—The moisture from wet clothes which have been "hung out to dry" evaporates more rapidly in hot dry weather.

Explanation.—The Theory Of Evaporation is this: The molecules of all substances which are at temperatures above 0 deg. absolute, that is which contain heat energy, are (Sec. 45) in continuous motion. In the case of a liquid, the motion of the molecules is rapid and occurs throughout the entire body of the liquid mass. Now, while these rapid molecular movements are occurring, certain liquid molecules collide continually with others which are similarly vibrating about rapidly. Due to the impact of these collisions, some molecules attain velocities much greater than the average velocity of the molecules in the mass. If the molecules which thus have acquired velocities greater than the normal happen to be near the surface of the liquid, then they may be projected (Fig. 287) out into the space above the liquid. Thus they become gas or vapor molecules. In the aggregate they form a vapor in the space above the liquid. During the process of evaporation into air, the space above the liquid is occupied by a mixture of air molecules and vapor molecules. The vapor molecules occupy portions of the large (relatively) spaces between the air molecules.

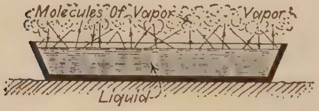


Fig. 287.—Illustrating evaporation or surface-vaporization.

297. When The Liquid Is Unconfined The Flying Off Of The High-velocity Molecules Continues until, ultimately, all of the liquid molecules disappear. Then complete vaporization has occurred. The liquid has "evaporated."

NOTE.—WHEN HEAT IS ADDED TO THE LIQUID—when it is warmed—the velocity of its molecules is increased and its evaporation is thereby hastened.

298. The Laws Of Evaporation are: (1) *It increases with the temperature.* (2) *It increases with the extent of surface exposed by the liquid.* (3) *It is much greater into dry air than into air which contains vapor. That is, it decreases as the saturation increases* (Sec. 305). (4) *It increases with the rate of removal of the vapor from the surface of the liquid* as some vapor molecules near the liquid surface tend to return to the liquid body if the vapor is not removed. (5) *The rate of evaporation is increased by diminishing the pressure on the exposed liquid surface* and vice versa. (6) *The rate of evaporation depends on the nature and concentration of any substances which may be dissolved* (Sec. 286) *in the liquid.* Formulas for computing the actual rate of evaporation of water under various conditions are given in the author's STEAM POWER PLANT AUXILIARIES AND ACCESSORIES.

299. Evaporation Increases With The Temperature Of The Liquid.—This follows since (Sec. 55) an increase in the temperature of the liquid is equivalent to an increase in the average velocity of molecular motion of the liquid molecules. When the temperature of a liquid is increased, the number of liquid molecules, which in a given time attain the high velocity which is necessary to project them into the space above the liquid, is increased correspondingly. Thereby the evaporation is increased.

EXAMPLES.—Wet objects dry more rapidly when placed on a radiator or near a hot stove. Damp objects are dried quickly by passing a hot iron over them; a cold iron has no effect. A sprinkled street pavement on which the sun is shining will dry promptly while one in the shade will remain wet.

300. Temperatures May Be Decreased By Evaporation (Fig. 288). When a certain weight of a liquid is vaporized, by evaporation or otherwise, then an amount of heat equal to the *latent heat of vaporization* of that weight of the liquid is abstracted from the liquid and air and objects which are adjacent to it (latent heat of vaporization is discussed in following Sec. 322). Thereby the remaining liquid and adjacent bodies are cooled. There are many practical examples of this phenomenon. A few are given below.

EXPLANATION.—Evaporation is in reality an escape, from the surface of the liquid, of those liquid molecules which have acquired the highest velocities—which represent the greatest heat energy per molecule. Hence, the continual projection of these molecules from the liquid results in a correspondingly continual decrease in the average velocity—temperature—of the molecules which remain. The temperature of the remaining liquid will therefore decrease until no more heat is lost from it by evaporation than it receives from surrounding objects.

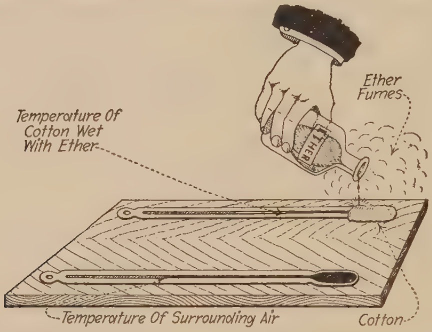

Ether Fumes
Temperature Of Cotton Wet With Ether
ETHER
Temperature Of Surrounding Air
Cotton

FIG. 288.—Illustrating the cooling effect of evaporation.

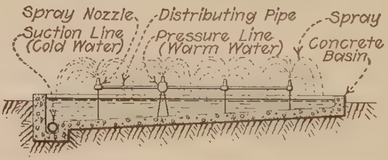


FIG. 289.—Spray cooling pond. The evaporation from the sprays and from the surface of the pond cools the water.

EXAMPLES.—A small quantity of ether dropped on the back of the hand will evaporate very quickly: Coincidentally, an intense cooling sensation will be felt where the ether touches the hand. If the ether is dropped on cotton (Fig. 288) which is wrapped around a thermometer bulb, the thermometer will indicate an immediate and pronounced temperature decrease. The temperature of condenser circulating water, which is used over and over again, is reduced by evaporating a small portion of it in a *cooling pond* (Fig. 289), *a cooling tower* (Fig. 290) or with spray nozzles (Fig. 291). Drinking water is kept cool in hot dry localities by placing it in a porous earthenware jar (Fig. 292) which is hung in a shady windy place; the water which seeps through to the surface of the porous jar is evaporated and thereby the remaining water in the jar is maintained cool. The evaporation from a specially constructed porous earthenware vessel (Fig. 293), which has been submerged in and saturated with, water, maintains at a relatively low temperature the food contained therein. Solid carbon dioxide may be made by the cooling effect of liquid carbon dioxide evaporating in a bag (Fig. 294).

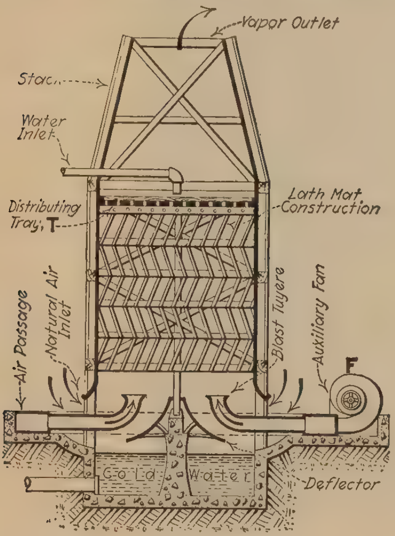


Fig. 290.

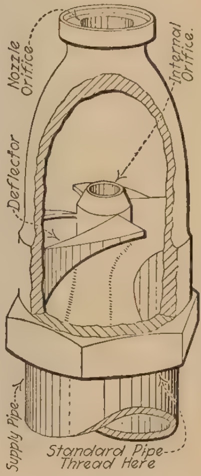


Fig. 291.

Fig. 290.—Cooling tower. (Warm water enters the distributing tray, *T*, and falls in fine streams over the lath checker-work. A current of air from the fan, *F*, along with some air drawn in by natural draft cools the falling water by evaporation.)

Fig. 291.—Spray nozzle with part of side cut away. (The nozzles break the water into fine droplets, thus exposing a large surface for contact with the air thereby causing rapid evaporation.)

Example.—Freezing Water By The Evaporation Of Ether may be effected with the apparatus shown in Fig. 295. The beaker is placed on a thin film of water on the wooden block. The block serves as a heat insulator. By blowing air through the ether with the bellows, the ether is evaporated rapidly. It absorbs the heat required for its evaporation from adjacent objects. Thereby the water film is transformed to ice: The beaker is "frozen" to the block with a layer of ice. In refrigeration plants, the evaporation of the liquid ammonia in the cooling coils (Fig. 296) abstracts (indirectly, see Div. 18 on Refrigeration) heat from the water in the freezing cans. Thus the water in the cans is changed into ice.

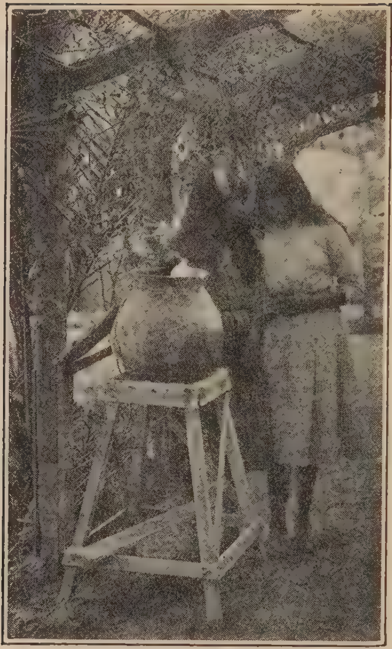


Fig. 292.—Porous earthen water jar or "olla" used for cooling water in hot dry climates. (Courtesy Santa Fe Railroad.)

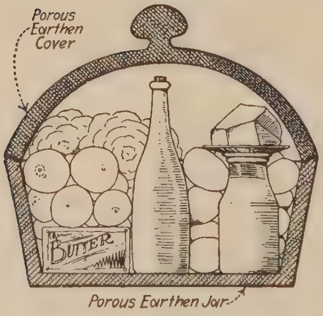


Fig. 293.

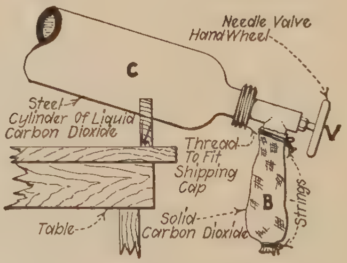

Needle Valve Hand Wheel
C
Steel Cylinder Of Liquid Carbon Dioxide
V
Thread To Fit Shipping Cap
B
Strings
Solid Carbon Dioxide
Table

Fig. 294.

Fig. 293.—Porous earthen cooling vessel. Food articles are placed inside. Entire vessel is then submerged in water for about 3 min. Water soaks into porous walls. Subsequent evaporation of water from outside of walls produces cooling effect.

Fig. 294.—Method of making solid carbon dioxide. (Opening *V* permits liquid carbon dioxide to flow into cloth bag *B*. Its rapid vaporization therein, due to the reduced pressure, causes the formation of carbon-dioxide snow in *B*.)

301. Condensation is the opposite of vaporization. It is the process by which a substance changes from the gaseous to the liquid or solid state. As explained hereinafter, condensation of a vapor may be due to either an abstraction of heat (cooling) when the pressure remains constant or to compressing the vapor when the temperature remains constant. Or it may be due to a combination of the two conditions.

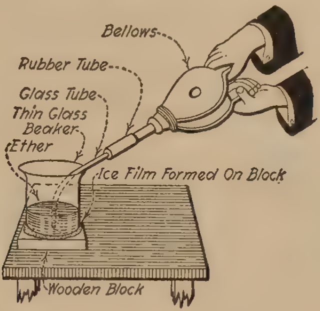


FIG. 295.—Water frozen by the rapid evaporation of ether.

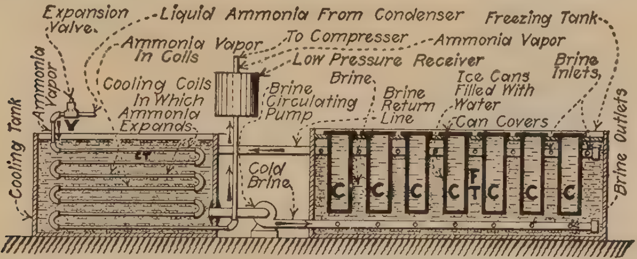


FIG. 296.—Diagram of cooling coils and brine system used in making "can" ice. (Liquid ammonia, when released through V, vaporizes and abstracts heat equivalent to its latent heat of vaporization from the brine in CT. The brine is then circulated through the freezing tank FT. Thereby the water in the cans, C, is frozen.)

EXAMPLES.—In the condenser (Fig. 297) in a steam-power plant, the steam is condensed into water by abstracting heat from it with cold water. Economies, as explained in Div. 15 result from the condensing operation. In a compression refrigeration plant (see Div. 18), the compressed ammonia vapor is condensed into liquid ammonia in an ammonia condenser.

302. All Substances Increase In Volume When Vaporized And Decrease In Volume When Condensed.—That is, their volumes increase (Fig. 298) when they are transformed from the liquid to the gaseous state and decrease when they are transformed from the gaseous to the liquid state. All substances (Table 303) undergo very great changes of volume while vaporizing or liquefying at moderate pressures.

EXAMPLES.—One (1) cu. ft. of water at 212° F., will expand into about 1,604 cu. ft. of steam at atmospheric pressure; see also Fig. 298. Also, 9.47 cu. ft. of carbonic acid gas (carbon dioxide or CO_2), at 32° F., in a manometer gas tank, will contract into 1 cu. ft. of liquid carbonic acid when condensed into a steel drum.

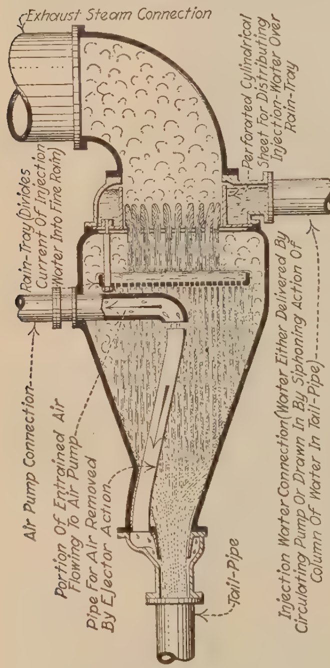

Exhaust Steam Connection
Perforated Cylindrical Sheet For Distributing Injection-Water Over Rain-Tray
Rain-Tray (Divides Current Of Injection Water Into Fine Rain)
Air Pump Connection
Portion Of Entrained Air Flowing To Air Pump
Pipe For Air Removed By Ejector Action
Tail-Pipe
Injection Water Connection (Water Either Delivered By Circulating Pump Or Drawn In By Siphoning Action Of Column Of Water In Tail-Pipe)

FIG. 297.

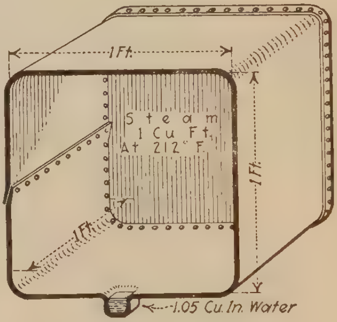


FIG. 298.

FIG. 297.—Sectional view of Wheeler barometric ejector condenser.

FIG. 298.—Showing relative volumes of the same weight of steam and water. (At 212° F. and 14.7 lb. per sq. in. pressure, 0.000,607 cu. ft.—or 1.05 cu. in.—of water will make 1 cu. ft., or 1,728 cu. in. of steam.)

303. Table Showing Specific Volumes Of Various Substances In The Liquid and Gaseous States. (Marks' MECHANICAL ENGINEERS' HANDBOOK.)

Material	Boiling pressure, lb. per sq. in. abs.	Boiling temperature, deg. Fahr	Specific volume = cu. ft. per lb.		Ratio = $G \div L$
			L Liquid	G Gas	
Water	14.7	212	0.0167	26.79	1604
Ammonia	14.7	−27.2	0.0237	18.02	760
Carbon dioxide	503.5	32	0.01759	0.1666	9.47
Sulphur dioxide	14.7	13.7	0.01130	5.38	477

304. Vapor Pressure Or Vapor Tension (Fig 299) is the pressure exerted by a body of vapor. It may be conveniently measured in pounds per square inch, inches mercury column, or in any other pressure unit (Sec. 7). The molecules comprising the vapor of a vaporized liquid act (Sec. 50) precisely as do those of a permanent gas. They produce a pressure by bombardment of the walls of any enclosing vessel.

EXAMPLE.—The most important example of vapor pressure is the pressure exerted by steam (Fig. 299) which is aqueous or water vapor.

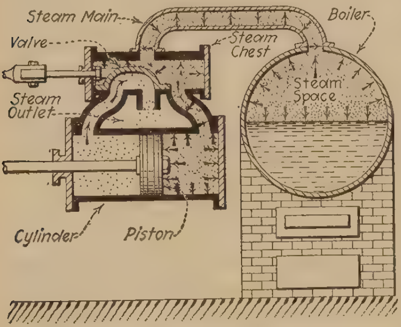


FIG. 299.—Vapor pressure exerted by water vapor (steam) on confining walls.

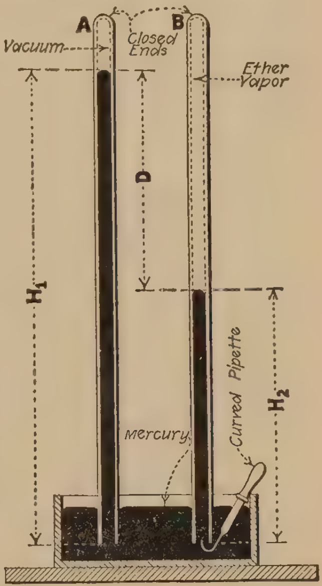


FIG. 300.—Illustrating the principle of vapor pressure.

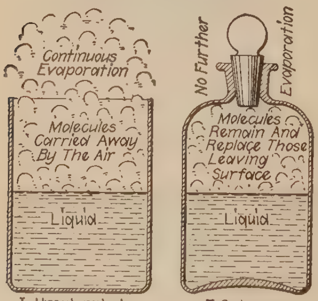
EXAMPLE.—Tube *A* in Fig. 300 in reality constitutes a barometer as explained in Sec. 10. The height of mercury column, H_1, is the height which is supported by the atmospheric pressure. If now a drop of ether be introduced into the tube with a curved pipette, as shown at *B*, the mercury column will immediately be forced down to the height H_2. The difference, *D*, in the heights of the two mercury columns will be the vapor pressure, expressed in inches mercury column, which is exerted by the ether vapor. The bombardment of the ether-vapor molecules creates the pressure which forces the mercury column down. The pressure of saturated ether vapor at room temperature may be as great as 16-in. mercury column.

NOTE.—VAPOR PRESSURE IS EXERTED WHEREVER THERE IS A VAPOR.—While the effects of vapor pressure are most apparent when the vapor is confined in a closed vessel such as a steam boiler or a closed-end tube like that of Fig. 300, an unconfined vapor exerts a pressure, just as does any gas, on the objects in and around it. Thus, water vapor in the air exerts a part of the observed pressure on the earth's surface—land and water—and on all objects in the locality where the vapor exists.

Example.—Suppose the atmospheric pressure as shown by a barometer is 14.5 lb. per sq. in. and that the air is mixed with saturated water vapor at 80° F. The vapor pressure due to aqueous vapor at 80° F. is (by a steam table) about 0.5 lb. per sq. in. Hence, the pressure due to the oxygen, nitrogen, and other relatively non-condensable constituents of the air is $14.5 - 0.5 = 14.0$ *lb. per sq. in.* That is, a cubic foot of the air will contain only as much of the non-condensable gases as if it were free of water vapor and at a pressure of 14 lb. per sq. in. When the quantity of a gas which is over water is being measured, this effect must be considered.

305. A Saturated Vapor is any vapor which cannot have heat abstracted from it or be compressed at constant temperature without partially condensing. That is, a vapor is saturated when its molecules are so densely packed in the given space that additional molecules arising from the liquid would tend to reduce the molecular arrangement to that which exists in the liquid state of the substance. See also Sec. 354 for another definition of saturated vapor.

Note.—When A Vapor Is Saturated, The Pressure Exerted By The Vapor presses, as it were, down on the liquid and, in effect, prevents further liquid molecules from entering the space where the vapor exists. There is an equilibrium between the pressure exerted by the vapor and the pressure exerted by the liquid. A vapor which is confined in a closed vessel may and will become saturated (Fig. 301-*II*) provided that a portion of the liquid remains in the vessel. But a vapor which is unconfined (Fig. 301-*I*), which is free in the open air, cannot become saturated because the vapor molecules diffuse and seep away through the air (note under Sec. 304) and are wafted away by air currents.


Continuous Evaporation
Molecules Carried Away By The Air
Liquid
No Further Evaporation
Molecules Remain And Replace Those Leaving Surface
Liquid

I-Unsaturated Vapor

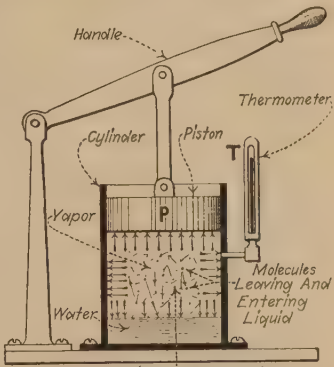
II-Saturated Vapor

Fig. 301.—Showing how confining vapor prevents further evaporation.

Explanation.—The water in the closed cylinder (Fig. 302) is assumed to be in process of vaporization at a certain temperature, T. Due to the violence of their vibratory motion, the liquid molecules at the surface are (Sec. 296) incessantly darting into the space between the water and the piston. Thus they become vapor molecules. But, while darting hither and thither in the enclosed space, some of these vapor molecules strike the surface of the water. These molecules thereby resume their original status as water molecules.

For a time, a greater number of molecules will be leaving the water to become vapor molecules than will be returning thereto to again become liquid molecules. The disparity between the number of departing and the number of returning molecules will, however, gradually diminish. Finally, the number of molecules arising from the water as vapor will equal the number returning thereto as liquid.

Hence, if the piston is still maintained in its original position, the total number of vapor molecules in the space between the piston and the water will thenceforth continue constant. When this condition of equilibrium is attained, the vapor is saturated.



Arrows Indicate Pressure Due To Bombardment Of Confining Surfaces By The Vapor Molecules

Fig. 302.—Illustrating principle of vapor-saturation.

Note.—The Word "Saturation" Is Commonly Used To Indicate The Condition Of The Aqueous Vapor In The Air In Any Space Into Which Water Has Vaporized.—In such cases the air is incorrectly said to be saturated with the vapor. (Instead it should be said to be *mixed* with saturated vapor.) This "saturated-with-the-vapor" idea is the popular, though scientifically inaccurate, interpretation of the term. It results from an erroneous theory, which formerly prevailed, that air preserves the vaporized condition of a substance by holding, like a sponge holds water, the vapor molecules suspended in the pores or spaces between its own (the air's) molecules. The following terms are (Psychrometric Tables, W. B. No. 235; *U. S. Department Of Agriculture*) incorrect: "The air is partly saturated with moisture." "Weight of aqueous vapor in a cubic foot of saturated air." The following is correct: "Weight of a cubic foot of saturated aqueous vapor." That is, the air is not "saturated;" it is the vapor which is saturated.

Example.—Steam in a boiler which is under pressure, assuming of course that there is water in the boiler in contact with the steam, is a good example of saturated aqueous vapor. In fact, such is called saturated steam.

306. Dalton's Laws For Vapors, discussions of which follow, are: (1) *The pressure of a saturated vapor depends only on its temperature.* (2) *The total pressure of a mixture of gases or vapors which have no chemical action on each other, is equal to* *the sum of the pressures which each would exert seperately if it were alone in the space occupied by the mixture.* These laws are stated a little differently by various authorities but the differences are of minor importance—the laws, as stated here, are believed to enumerate the governing facts.

Note.—The Second Of The Above Laws Is Called "Dalton's Law Of Partial Pressures."—The law does not hold for vapors of liquids which dissolve in one another either partially or in all proportions (Gregory and Hadley, Manual Of Mechanics And Heat, p. 237). See discussion of this law as applied to gases in Sec. 276.

Example Of Exception.—Gasoline is a mixture or solution of many liquids having different boiling points (Sec. 315). The vapor pressure of each of these liquids is sufficient so that if the combined vapor pressure were the sum of the individual vapor pressures, a pressure of much more than atmospheric pressure would be developed and the liquid would boil at ordinary temperatures. Similarly it would be impossible to condense the gasoline vapor as it is condensed in its purification by distillation. The combined vapor pressure of the gasoline constituents is more nearly an average than a sum of their individual vapor pressures.

307. The Pressure Of A Saturated Vapor Depends Only On Its Temperature.—If enough ether is introduced into tube *B* of Fig. 300, so that it does not all vaporize at atmospheric temperature, then *D* will measure the pressure, in inches of mercury column, of the *saturated* ether vapor at that temperature. If, then, the saturated vapor in *B* be warmed by passing a bunsen-burner flame across it, more of the ether will be vaporized and the vapor will then exert a greater pressure and force the mercury still further down. Cooling the vapor has the opposite effect. By measuring the pressures exerted by the vapor at different temperatures, it can be shown that the pressure (Sec. 308) of a saturated vapor is determined only by its temperature. The pressure is independent of its volume if the temperature remains as shown above, the vapor determines its own volume for any given temperature.

Example.—By referring to a saturated-steam table (Sec. 394) it will be noted that for each pressure there is a definite temperature and vice versa. A saturated-steam table is merely a saturated-water-vapor table.

Explanation.—For each temperature of a gas or vapor, there is (Sec. 55) a certain speed of vibration of its molecules. Since the vibration speed of the molecules determines the pressure which the gas exerts it follows that the pressure is determined by the temperature. If the temperature of the vessel which contains the vapor is raised, the molecules are projected more frequently from the liquid. Hence, more vapor molecules must then accumulate above the liquid to insure equilibrium between the vapor and its liquid. Thereby the number of molecules in the vapor space is increased. Furthermore, their velocities are increased by the temperature increase. Hence the pressure exerted by the vapor is increased correspondingly.

308. The Saturation Pressure Of A Vapor is defined as the pressure which, at a given temperature, the vapor exerts when completely saturated. The saturation pressure is the maximum pressure which a vapor can exert at any given temperature. Saturated-steam tables (Sec. 394) give the saturation pressure for water vapor or steam.

309. Condensation Occurs When Heat Is Abstracted From A Saturated Vapor Or When Vapor Is Compressed Without Changing Its Temperature.—Examination of any saturated-vapor table (Div. 11) will disclose that the density (weight of a cubic foot) of saturated vapor increases with its temperature. Now, if heat is abstracted from a saturated vapor, the vapor will be cooled and will contract—as all substances do when their temperature is decreased. Or, if the saturated vapor is compressed, its temperature remaining constant, it will then also occupy a smaller volume. Hence, abstracting heat from or compressing a saturated vapor causes a given weight of the vapor to occupy less volume—that is, increases the density of the vapor. But, by the vapor tables, the density of the vapor cannot have a value greater than given in the table for the given temperature. Therefore, a portion of the vapor must condense and occupy only that smaller volume which it requires when in the liquid state. If the vapor has been compressed without changing its temperature, then the resulting mixture of liquid and vapor will still exert the same vapor pressure as before compressing the vapor; but the vapor will now occupy a smaller volume than before. If the vapor has suffered an abstraction of heat, it may exert a smaller pressure and exist at a lower temperature than before heat was abstracted from it.

NOTE.—HEAT IS ABSTRACTED FROM WATER VAPOR IN A STEAM CONDENSER.—Steam may, after being used by an engine or turbine, be admitted to the condenser which is maintained at a low temperature by circulating cold water through it. The exhaust steam is thus cooled to a relatively low temperature at which it can exert only a small pressure and has a smaller density. The greater portion of the exhaust steam from the engine or turbine is thereby condensed—only a small weight of the original vapor remaining as vapor in the condenser. How economies may result through the operation of a condenser in connection with an engine or turbine is explained in Sec. 513.

Explanation.—Imagine a closed vessel which contains a liquid and its vapor at a certain temperature. The vapor is saturated because it is in contact with the liquid and molecules are passing from the liquid into the vapor at the same rate as molecules are passing from the vapor into the liquid (as explained under Sec. 305). If, now, the vessel is cooled from without, the liquid will first be cooled (because it is a better conductor of heat than the vapor). Thus, the average velocity of the liquid molecules will be decreased. Less of the liquid molecules will then have that abnormal velocity which is necessary to project them into the space above the liquid level. But, for the instant at least, the vapor molecules still possess the same velocities as before heat was abstracted. Hence, the equilibrium between the number of molecules passing into and out of the liquid is temporarily destroyed.

Now more vapor molecules will enter the liquid than leave the liquid. Hence, the more rapidly moving vapor molecules enter the liquid—tending to increase the temperature of the liquid and decrease that of the vapor. But heat is being withdrawn from the liquid. Hence, the liquid temperature is not increased by the entering vapor molecules but the liquid temperature remains constant until the vapor and liquid attain the same temperature. By this time enough vapor molecules have entered the liquid (in excess of those which have left the liquid) to decrease the temperature of the vapor to such a point that equilibrium is again restored—the number of molecules entering and leaving the liquid is again the same. But, during this process, more molecules have been entering the liquid than have been leaving it. Hence, a portion of the vapor has been condensed.

310. Two Or More Vapors, When Mixed, Do Not Affect The Saturation Point Or Vapor Pressure Of Either provided the vapors do not act chemically on one another nor mix by solution (Sec. 169) when condensed. The presence of more than one vapor simply has a retarding effect on the time necessary for a vapor to become saturated. The same amount of liquid will evaporate into an air-filled space as into a vacuum of the same volume. The air merely retards the rate of evaporation.

Explanation.—The molecules of any gas or vapor have considerable space between them. The molecules of the second vapor occupy portions of these empty spaces. It is evident, from the theory of molecular motion of gases, that the molecules in vaporizing from a liquid must encounter opposition by colliding with the molecules of the second vapor. Hence, due to the thus retarded motion, the time necessary for sufficient molecules to pass from the liquid to produce saturation is increased. It follows that complete saturation of a space wherein a partial vacuum exists is accomplished with greater rapidity than where the space is filled with air or other gas.

311. The Effect Of The Air In Retarding The Rate Of Evaporation is important. If water vapor, which is constantly evaporating from river, lake, and ocean, diffused rapidly, the atmosphere would always be completely saturated (100-per cent. humidity, Sec. 331). All absorbent objects about us would then be soaked continually with moisture. But, because of its very slow dissemination, relatively little water vapor is contained in the atmosphere—even in regions adjacent to large bodies of water. A portion of that water vapor which does exist in the atmosphere always condenses (Sec. 339) when the temperature falls to the saturation point (Sec. 305). Some one of the weather phenomena described in Sec. 339 then results.

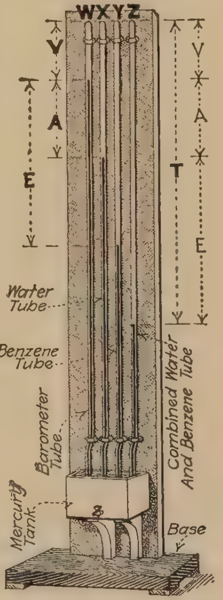


Fig. 303.—The combined pressure of two vapors is equal to the sum of their individual pressures.

312. The Combined Pressure Of Two Or More Vapors Or Gases Which Occupy The Same Space Is Equal To The Sum Of The Individual Pressures Exerted By Each.—This is the second of Dalton's laws (Sec. 306). Its truth may be readily verified experimentally as is explained below:

Example.—In Fig. 303, *W* is an ordinary barometer tube with the usual vacuum space, of length *V*, above the mercury. All of the tubes *W*, *X*, *Y*, and *Z* are of identical construction. Into the space above the mercury in *X* enough water has been introduced to produce a saturated vapor, lowering the mercury level by distance *A*. Similarly, benzene vapor in *Y* lowers the level by distance *E*. Now, if an excess of water and of benzene were introduced into *Z*, the two combined saturated vapors would lower the mercury by distance *T*. Now it will be found that: $T = V + A + E$ (nearly). This proves that the combined pressure of the water vapor and the benzene vapor is nearly equal to the sum of their individual pressures.

313. Boiling Or Ebullition Is Vaporization From Within The Body Of A Liquid as well as from its surface. When heat is applied (Fig. 304) to a glass vessel which contains a transparent liquid, as clean water, bubbles will, after a time, be seen to form in that portion of the liquid which is immediately contiguous to the source of heat. These bubbles are composed of vapor, in precisely the same form as that which is generated by evaporation (Sec. 296) at the surface of the liquid.

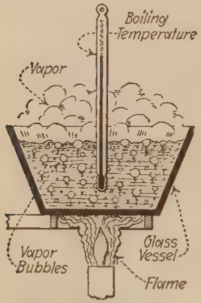


Fig. 304.—Illustrating boiling or internal vaporization.

Explanation.—The liquid in contact with the bottom of the glass vessel (Fig. 304) absorbs heat from the gas flame. The vibratory motion (Sec. 45) of the molecules in this portion of the liquid mass is thereby intensified. Certain molecules attain very high velocities and, colliding, are thus "bounced" to comparatively great distances from one another. Certain of these separated molecules then assemble in groups and assume the mutual arrangement which is peculiar to the vaporous condition of matter. The bubbles, which may be seen through the transparent wall of the vessel, are the visible manifestation of this arrangement. Being less dense—lighter—than the surrounding liquid, these bubbles, or groups of vaporized molecules, tend (Sec. 137) to rise toward the upper surface. That is, a condition of boiling or ebullition ensues.

If the liquid mass is of considerable depth, the bubbles which are first formed may disappear before they reach the upper surface. When this happens, the bubbles have simply given up the heat, to which they owe their vaporous form, to the molecules of the cooler portions of the liquid through which they have passed. They have (Sec. 162) condensed. That is, they have resumed the molecular arrangement peculiar to the liquid state.

Due to this process of convection (Sec. 137) the entire mass of the liquid presently acquires a practically uniform temperature. Hence, the bubbles which are subsequently formed at the bottom of the vessel will retain their heat and, incidentally, their vaporous structure until they rise to the upper surface where they will break and their vapor will then mingle with the vapor above.

Note.—All Of The Bubbles Which Form In A Boiling Liquid May Not Be Vapor Bubbles.—Some of them may be due to the presence of air in the liquid. Application of heat to an air-impregnated liquid will cause minute masses of the air to expand and form bubbles.

NOTE.—WHEN A LIQUID BOILS THE MOLECULES PASS INTO THE VAPOROUS CONDITION BOTH AT THE FREE SURFACE OF THE LIQUID AND AT THE SURFACES OF THE VAPOR BUBBLES within the liquid. Thus, there is an essential difference between boiling and evaporation. In evaporation (Sec. 296) the molecules pass to the vaporous condition only at the free surface. The only reason (Millikan & Gale) why vaporization takes place so much more rapidly at the boiling temperature than just below it is that the bubbles first form at the boiling temperature and the evaporating surface is increased enormously by the bubbles as soon as they form.

314. Table Showing Boiling Temperature Of Liquids At Atmospheric Pressure. See Table 350 for boiling temperature of various liquefied gases. (MARKS' MECHANICAL ENGINEERS' HANDBOOK.)

Liquid	Temperature, in deg. Fahr.	Liquid	Temperature, in deg. Fahr.
Zinc	1,680	Aniline	363
Sulphur	823	Calcium chloride (sat. sol.)	356
Mercury	675	Turpentine	320
Paraffin	572	Toluene	230
Glycerine	554	Sodium chloride (sat. sol.)	226.4
Phosphorus	554	Water	212
Linseed oil	538	Alcohol	172.4
Naphthalene	424	Helium	−450

315. Every Liquid Has, For A Given Impressed Pressure, A Definite Boiling Temperature.—When a thermometer is inserted in a mass of liquid to which heat is being applied (Fig. 304), the mercury will rise until the liquid begins to boil. The mercury—temperature—will then become stationary and will stay so (as long as there is liquid in the vessel and the pressure on the surface of the liquid remains constant) no matter how great the rate of heat application. Why the temperature thus remains constant is explained in Sec. 96 and Sec. 98. For a given liquid and a given pressure, this boiling temperature or boiling point is always the same; see Table 314.

NOTE.—THE REASON THE TEMPERATURE OF THE LIQUID CANNOT BE INCREASED ABOVE THE BOILING POINT is that the area of surface of the bubbles always increases to just such an extent that the loss of heat necessary to do the disgregation work which is required to affect vaporization is exactly equal to the heat received from the fire. In other words, the disgregation heat continually passing out with the ascending vapor molecules becomes just equal to the heat which is being continually supplied by the heat source. Thus, constant temperature and a *heat balance* are maintained.

316. The Boiling Temperature Is The Temperature At Which The Pressure Of The Saturated Vapor Equals The Pressure Existing Outside Of And Imposed On The Surface Of The Liquid.—This pressure is, when the vessel is wide open to the air, the atmospheric pressure. When the vessel is closed, the pressure is that due to the liquid vapor (usually steam) in the vessel plus the pressure of the air or any other gas which may be present.

EXAMPLE.—When a steam boiler is first placed in operation and has air in its steam space, the air pressure imposed on the water surface may be considerable (up to atmospheric pressure). But after the boiler has been operated for a short time, practically all of the air is displaced and the pressure then imposed on the liquid surface is due almost wholly to the vapor pressure of the liquid.

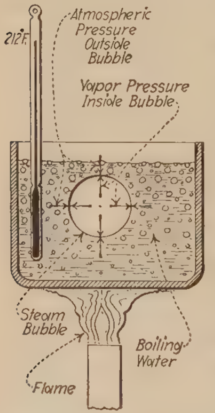

212°F.
Atmospheric Pressure Outside Bubble
Vapor Pressure Inside Bubble
Steam Bubble
Boiling Water
Flame

FIG. 305.—Vapor pressure within steam bubble equals pressure imposed on outside of bubble.

EXPLANATION.—As stated previously, the formation of vapor bubbles is the visible manifestation of and is essential to boiling. Now it is evident that the vapor pressure of the vapor (Fig. 305) within each bubble must (disregarding the small additional impressed pressure due to the thrust of the liquid itself) be the same as the pressure—often the atmospheric pressure—which presses on the surface of the liquid. The inside vapor pressure and the outside impressed pressure must exactly equal each other—otherwise the bubble would collapse. Now (Sec. 315) a certain definite temperature is required for the production of each vapor pressure. Therefore it is evident that bubbles cannot form until the temperature of the liquid is such that the pressure which its vapor exerts is exactly equal to the impressed pressure. Hence, the boiling temperature of a liquid—the temperature of bubble formation—must be that temperature at which the vapor pressure equals the impressed pressure.

317. The Effect Of Change Of Pressure On The Boiling Points Of Liquids (See Table 318) will now be considered. If a boiling liquid is subjected to additional pressure, the boiling will cease and the temperature will again rise as the application of heat is continued. Ultimately, a new temperature—which corresponds to a new pressure—will be attained at which boiling will again commence. The greater the pressure the greater the boiling point (Fig. 306) and vice versa.

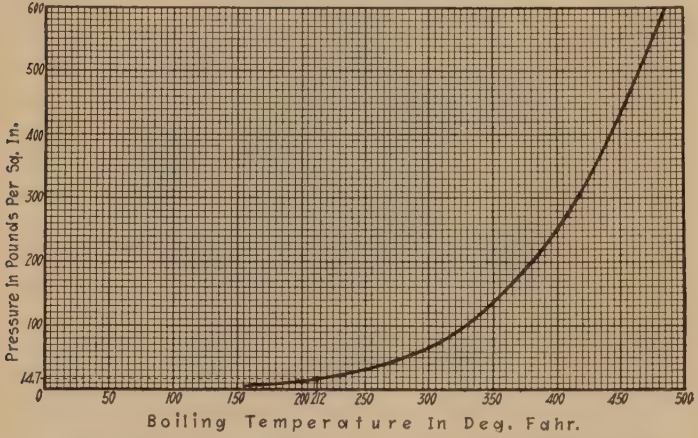


FIG. 306.—Graph showing relation of boiling temperature of water to pressure.

EXAMPLE OF THE EFFECT ON BOILING TEMPERATURE OF INCREASING THE PRESSURE.—In Fig. 307, heat is imparted to water in *A*. Thereby the water in this cylinder is boiled. In the end of the cylinder fits a piston, *P*, which has sufficient weight to maintain a pressure of about 5 lb. per sq. in. gage within the cylinder. The sliding piston maintains the pressure constant. When the heating is begun, the piston rests on the surface of the cool water and the thermometer, *T*, indicates a low temperature—the temperature of the cool water. As the heating is continued, the temperature rises to about (see steam table, Sec. 394) 228° F., which corresponds to a pressure of 5 lb. per sq. in. At this temperature boiling commences. No further rise in temperature is indicated by the thermometer nor does the pressure, as shown by the gage, *G*, increase. But as the vapor which is projected from the boiling water collects above it, more and more space is required by the vapor. This pushes the piston up in the cylinder until, if permitted to continue, it would force the piston out of the top. But the pressure and temperature remain constant.

Now, suppose that after the boiling, as shown in *A*, has continued for a time, the pressure within the cylinder is so increased by the addition of weight, *W*, that the gage will indicate constantly 10 lb. per sq. in.

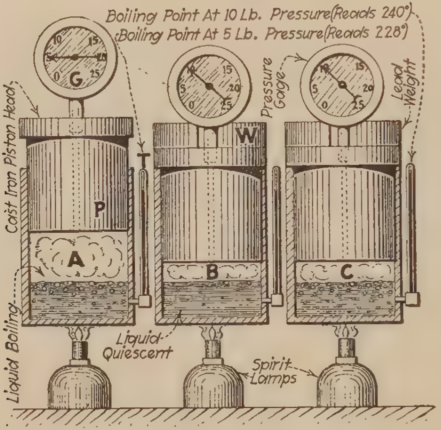
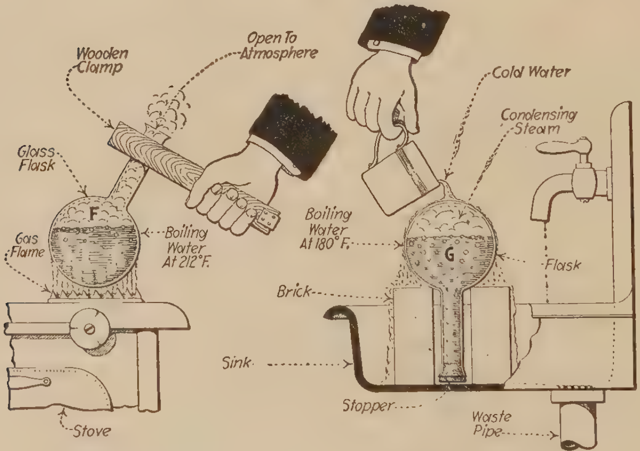


Fig. 307.—Illustrating effect of pressure on boiling points of liquids.



I-Water Boiling At 212 Deg. Fahr.

II-Water Boiling At 180° Deg. Fahr.

Fig. 308.—Experiment proving that the boiling point decreases as the pressure is decreased.

Immediately, the piston, which it will be assumed is resting half-way up in the cylinder, will be forced down. This reduces the volume of the vapor and, hence, increases its pressure. Due to this increased pressure, boiling at once ceases—there will be no vapor bubbles in the liquid in *B*. But, if the heating of *B* is continued, ultimately the new boiling temperature of about 240° F. (see steam table), which corresponds to the new pressure of 10 lb. per sq. in., will be attained as shown at *C*. Then,

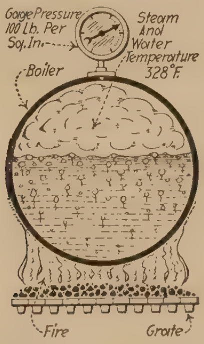

Gage Pressure 100 Lb. Per Sq. In.
Steam And Water Temperature 328°F.
Boiler
Fire
Grate

FIG. 309.—Illustrating effect of pressure on the boiling temperatures of liquids.

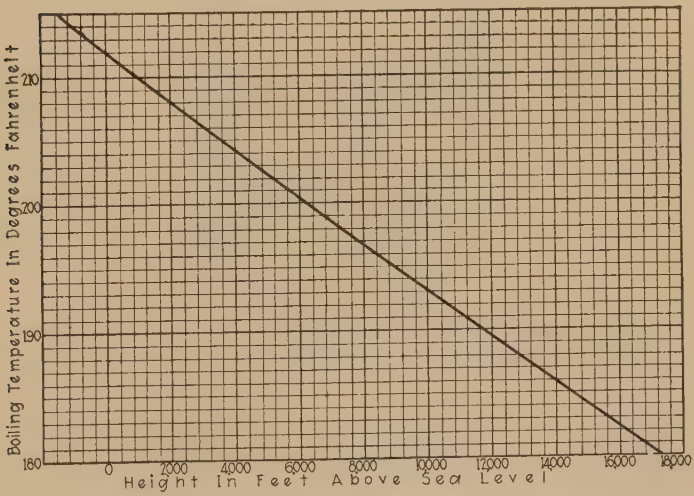


FIG. 310.—Graph showing variation of boiling temperature of water in accordance with variations of altitude above sea level.

the piston will again commence to rise as the boiling once more starts. Again, under these new conditions, the new temperature and the new pressure will remain constant.

EXAMPLE OF THE EFFECT ON BOILING TEMPERATURE OF DECREASING THE PRESSURE.—First, the water in the flask *F* (Fig. 308) is boiled.

Then the flask is removed from the flame, corked, and inverted as at *G*. The temperature of the hot water in the flask soon falls to below 212° F. and the boiling ceases. But if now some cold water be poured over the flask, as shown, the water in the flask will commence to boil again. The cold water by condensing the steam in the flask decreases the impressed pressure. Thereby the water in the flask boils at a temperature lower than 212° F. But when sufficient vapor has been evolved in the flask to produce the vapor pressure which corresponds to the new lower temperature, the boiling ceases. This process of boiling and condensation may be repeated many times at successively lower temperatures, without reheating, by repeated water applications.

Example.—Water in a steam boiler, under ordinary atmospheric pressure, or 14.7 lb. per sq. in., boils (Table 318 or any steam table and Fig. 306) at 212° F. When the water has vaporized into steam until (Fig. 309) a pressure of 100 lb. per sq. in. gage is attained, the boiling temperature is then, as shown by any steam table (Sec. 394) 328° F.

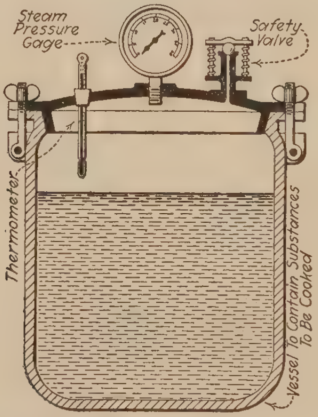


Fig. 311.—Pressure steam cooker. (Boiling of the water in the tightly-closed vessel generates steam, which is not permitted to escape. The steam increases the pressure within the vessel and thus raises the boiling point.)

Examples.—Water in an open vessel will boil on the top of a high mountain at a much lower temperature (Table 319 and Fig. 310) than at sea level. This is because of the lower atmospheric pressure (Sec. 9) at the high altitude. It requires a long time to cook eggs or vegetables by boiling on a high mountain top because of the low boiling temperatures at high elevations. This difficulty may be overcome by boiling the food in a closed vessel or in a pressure cooker (Fig. 311) whereby the boiling point of the contained liquid is raised by the self-generated internal pressure.

318. Table Showing Boiling Temperatures Of Water At Various Pressures. (From Marks and Davis' Steam Tables.)

Pressure, in lb. per sq. in.[a]		Boiling temperature, in deg. Fahr.	Pressure, in lb. per sq. in.[a]		Boiling temperature, in deg. Fahr.
Absolute	Gage		Absolute	Gage	
1	− 13.7	101.8	100	85.3	327.8
5	− 9.7	153.0	150	135.3	358.5
10	− 4.7	193.2	200	185.3	381.9
14.7	0.0	212.0	250	235.3	401.1
15	0.3	213.0	300	285.3	417.5
25	10.3	240.1	400	385.3	444.8
50	35.3	281.0	500	485.3	467.3
75	60.3	307.6	600	585.3	486.6

[a] *Absolute Pressure* = *Gage Pressure* + 14.7. *Gage Pressure* = *Absolute Pressure* − 14.7. The equations are true only when the pressures are expressed in pounds per square inch. See Sec. 18 for equations and explanation.

319. Table Showing Average Boiling Temperatures Of Water At Various Altitudes Above Sea-level. It should be understood that, at any elevation, the barometric pressure varies from time to time. At all times, the actual boiling point of water is that corresponding to the atmospheric or barometric pressure and may be accurately found in any steam table (Sec. 394).

Altitude, in feet	Boiling temperature, in degrees Fahrenheit	Altitude, in feet	Boiling temperature, in degrees Fahrenheit
−1,316 (Dead Sea).........	214	4,130....................	204
− 505....................	213	5,185....................	202
0 (Sea level)..........	212	6,250 (Mt. Washington)...	200
510....................	211	8,950....................	195
1,020	210	11,720....................	190
1,545	209	15,650 (Mont Blanc).......	184
2,050	208	17,337 (Himalayas)........	180
3,085	206		

320. The Boiling Temperature Of A Liquid Which Holds Another Substance In Solution may be either above or below the boiling temperature of the pure liquid. If the dissolved substance is a solid, the boiling temperature will be higher than that of the pure liquid. But if the liquid holds a gas or a more volatile liquid in solution, the boiling temperature will be lower.

Example.—When a quantity of water (*A*, Fig. 312) has dissolved (Table 321) as much salt as it can possibly hold in solution the boiling temperature at atmospheric pressure of the resulting brine (*B*, Fig. 312) will be about 227° F. When a quantity of water (*C*, Fig. 313) holds carbon-dioxide gas in solution, the boiling temperature of the solution (*D*, Fig. 313) will be less than 212° F.

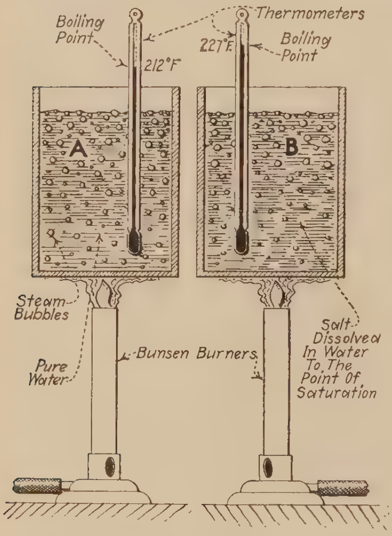


Fig. 312.—Illustrating the elevating effect of a dissolved solid on the boiling point of a liquid substance.

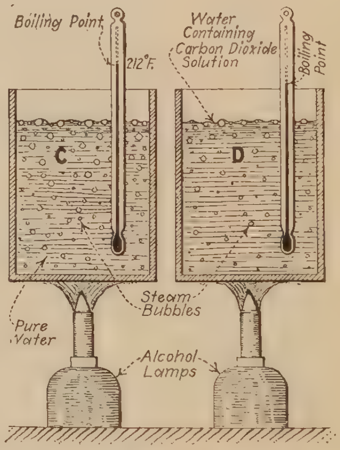


Fig. 313.—Illustrating the depressing effect, of a dissolved gas, on the boiling point of a liquid substance. (Steam bubbles only rise from the pure water whereas both steam and carbon dioxide bubbles rise from the solution.)

321. Table Showing Boiling Temperature Of Brine At Different Degrees Of Saturation.—Computed from Smithsonian Tables.

Units by weight of salt to 100 units of water	Temperature, deg. Fahr.
6.6	212
12.4	215.6
17.2	217.4
21.5	219.2
25.5	221
33.5	222.8
40.7	227.8

322. The Latent Heat Of Vaporization is, generally speaking, the heat which is (Sec. 106) required to change a liquid at a given temperature into a vapor at the same temperature. A very great quantity of heat is necessary to effect vaporization although no temperature change occurs. Specifically: The latent heat of vaporization of a liquid is the number of B.t.u. (Table 323) which is absorbed and necessary—to change 1 lb. of the liquid into vapor at the *same* temperature and pressure. (Refer to Sec. 289 for a discussion of latent heat of fusion which is a somewhat similar property.) See preceding explanation (Sec. 104) of how the heat expended in vaporization is largely employed in doing disgregation work—but some of the heat may also be expended in doing external work as is there explained.

Example.—Consider a closed vessel (Fig. 314) which has an escape valve, *V*, so adjusted that any vapor generated within the vessel will pass out at precisely the requisite rate to preserve a constant absolute pressure (Sec. 15) within the vessel of 14.7 lb. per sq. in. This is equivalent to 0.0 lb. per sq. in. gage pressure (Sec. 16). Exactly the same conditions would obtain if the vessel were located at the sea level (Sec. 9) and were open to the atmosphere.

Now, 1 lb. of water at 32° F. is placed in the vessel. It is heated with the spirit-lamp, *L*, flame. The mercury column in the thermometer will rise gradually until 180 B.t.u.—*MN*, Fig. 315—of heat (vibration heat) have been imparted to the liquid. The thermometer will then read 212° F. (Each B.t.u. will raise the temperature of the 1 lb. of water 1° F. Hence, 180 B.t.u. will increase it by 180° F. Therefore, the resulting temperature will be 32 + 180 = 212° F.) This increase in temperature is shown by *AB* in Fig. 315. The increase in temperature is due to vibration work (Sec. 97) which has been done by the heat on the water.

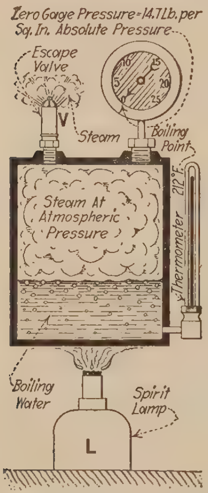

Zero Gage Pressure=14.7Lb. per Sq. In. Absolute Pressure
Escape Valve
V
5
10
15
20
25
Steam
Boiling Point
212°F.
Steam At Atmospheric Pressure
Thermometer
Boiling Water
Spirit Lamp
L

Fig. 314.—Vaporizing water under constant pressure.

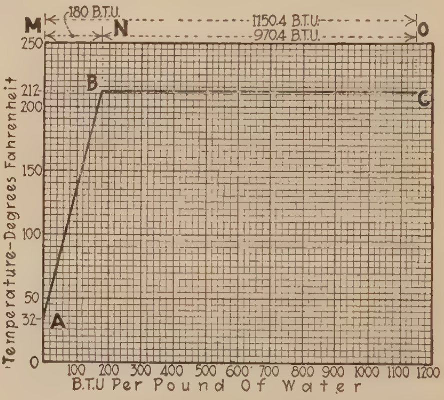


Fig. 315.—Illustrating latent heat of vaporization of 1 lb. of water.

When the water temperature attains 212° F. the imparted heat will commence to do disgregation work (Sec. 98) and the water will commence to boil—vaporize—because the boiling point of water at atmospheric pressure (14.7 lb. per sq. in.) is 212° F. Now as the lamp, *L*, continues to impart heat to the water, the heat will continue to do disgregation work and vaporization will continue. That is, steam will start forming when the water temperature first attains 212° F. and its formation will continue so long as heat (disgregation heat) is being imparted to the water. But while this vaporization ensues the temperature of the water will not rise above 212° F. (*BC*, Fig. 315) in spite of the fact that heat is being added continually to the water. The thermometer will stand stationary at the 212° mark until the water has been entirely changed into water vapor or steam. This is indicated by the line *BC* in Fig. 315. There will be required, so repeated experiments show, 970.4 B.t.u. (*NO*, Fig. 315) to change the 1 lb. of water at 212° into 1 lb. of steam at 212°.

The heat required (970.4 B.t.u. in this case) to change 1 lb. of the liquid at boiling temperature into vapor at the same temperature is the latent heat of vaporization of the liquid.

If the heating is continued, at the instant the last trace of the original 1 lb. of water flashes into steam, the thermometer mercury will begin to rise. The temperature rise will be due to the heat—vibration heat—which is absorbed by the steam and which will now manifest itself partly as vibration work (Sec. 97). That is, the steam becomes superheated (Sec. 356).

EXPLANATION.—Although the thermometer in Fig. 314 indicated no temperature rise while the vaporization was in progress, heat was, nevertheless, being transmitted continually from the flame to the water. But the energy of this latent (Sec. 106) or apparently inactive heat was spent partly in the work of disintegrating the molecular structure of the liquid molecules and in building up the new vapor-molecule structure (disgregation work, Sec. 98) and partly in expanding the molecules against external forces—the atmospheric pressure in this case (external work, Sec. 99). Therefore, this latent heat resides in the vapor in the form of potential molecular energy. It is transformed into the potential energy (Sec. 25) of position which the vapor molecules possess by virtue of their increased distance from one another. This phenomenon is similar to that of latent heat of fusion (Sec. 289) and is present in the vaporization of all substances.

EXAMPLE.—How much heat will be required, at atmospheric pressure, to vaporize 10 lb. of mercury which is at a temperature of 40° F.?

SOLUTION.—From Table 314, the boiling or vaporizing temperature of mercury is 675° F. From Table 90, the average specific heat of mercury is 0.033. Therefore, the heat necessary to raise the temperature of the 10 lb. of mercury from 40° F. to its vaporizing temperature is: $(675 - 40) \times 10 \times 0.033 = 218.6$ B.t.u. From Table 323, the latent heat of vaporization of mercury is 122 B.t.u. per lb. Therefore, to vaporize the 10 lb., there would be required: $10 \times 122 = 1{,}220$ B.t.u. Hence, the total heat necessary to raise the temperature and vaporize would be: $218.6 + 1{,}220 = 1{,}438.6$ B.t.u. Note that the greatest part of the total heat is necessary to effect vaporization and that comparatively little is used in raising the temperature of the mercury to the vaporizing point.

EXAMPLE.—How much heat will be required to: (1) Convert into water, a 201.5-lb. block of ice which is at 29° F.; (2) Raise the temperature of the resulting water to the boiling point at atmospheric pressure; (3) Vaporize the water under atmospheric pressure?

SOLUTION.—In an example under Sec. 292 it is shown that 29,186 B.t.u. are necessary to convert the 201.5 lb. of ice into water at 32° F., which is the melting temperature of ice. Now, from Table 90, the mean specific heat of water is 1.0. Also, from Table 314, the vaporizing temperature of water at atmospheric pressure is 212° F. Therefore, to raise the 201.5 lb. of water to the vaporizing temperature there would be required: $(212 - 32) \times 1.0 \times 201.5 = 36{,}270$ B.t.u. Since, the latent heat of vaporization of water at atmospheric pressure is (Table 323) 970.4 B.t.u. per lb., to vaporize this 201.5 lb. of water, there would be necessary: $201.5 \times 970.4 = 195{,}536$ B.t.u. Then, the total heat expenditure for melting the ice, raising the temperature of the water and vaporizing it is: $29{,}186 + 36{,}270 + 195{,}536 = 260{,}992$ B.t.u.

NOTE.—THE LATENT HEAT OF VAPORIZATION OF A LIQUID DIMINISHES AS THE TEMPERATURE AND PRESSURE, UNDER WHICH THE VAPORIZATION OCCURS, INCREASE.—It disappears entirely when (Sec. 349) the critical temperature and pressure are reached. See the vapor tables in Div. 11 for values.

323. Table Of Latent Heats Of Vaporization At Atmospheric Pressure. (MARKS' MECHANICAL ENGINEERS' HANDBOOK)

Material	Latent heat of vaporization, in B.t.u. per lb.	Material	Latent heat of vaporization, in B.t.u. per lb.
Acetone	233	Hydrogen	222
Alcohol	385	Methyl chlorine	175
Aniline	198	Mercury	122
Benzol	169	Nitrogen	81.5
Carbon bisulphide	152.5	Oxygen	92
Chlorine	112	Sulphur	650
Chloroform	110	Turpentine	126
Ether	162	Water	970.4

324. The Latent Heat Of Steam is the latent heat of vaporization (as defined above) of water and is equal to 970.4 B.t.u. at atmospheric pressure—14.7 lb. per sq. in. absolute—and the corresponding temperature of 212° F. See steam table 394 for other temperatures and pressures.

325. The Latent Heat Of Vaporization May Be Divided Into Two Parts: (1) *External latent heat of vaporization.* (2) *Internal latent heat of vaporization.* Both are defined below. Both of these latent heats are stored in the vapor and are given out when the vapor is condensed under the same external conditions as those under which it was vaporized. Values for these two heats, for the common vapors, are given in the tables in Div. 11. Thus:

$$\mathbf{L} = \mathbf{L}_E + \mathbf{L}_I \qquad \text{(B.t.u. per lb.)} \tag{241}$$

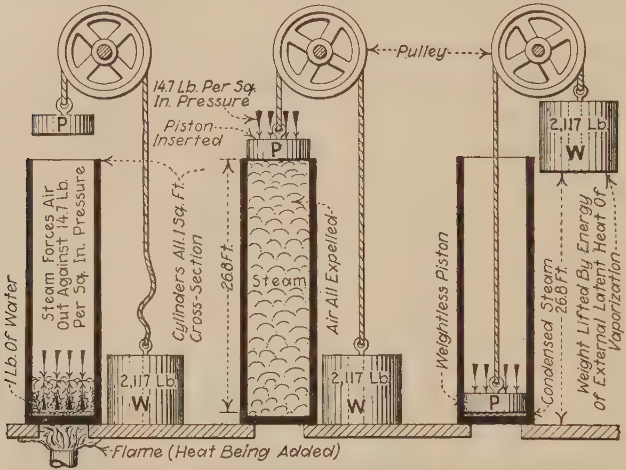
Wherein: $\mathbf{L}$ = latent heat of vaporization, that is, the total latent heat of vaporization, in British thermal units per pound. $\mathbf{L}_E$ = external latent heat of vaporization, in British thermal units per pound. L_I = internal latent heat of vaporization, in British thermal units per pound.

326. The Internal Latent Heat Of Vaporization, L_I, is the *disgregation* heat which must be added to the liquid to vaporize it, or which is given up by the vapor when it is liquefied. It is the heat energy which is expended in the internal work of overcoming the molecular cohesion of the liquid molecules which is necessary to change them into vapor molecules. It is the increase in internal heat energy which accompanies vaporization. As is shown by the values in the tables of vapor properties in Div. 11, the internal latent heat of vaporization decreases as the temperature, at which the vaporization occurs, increases. This is because the higher the temperature the more rapidly the molecules will be vibrating and the further they will be apart; hence, less heat will be required to disgregate into a vapor a liquid at a high temperature than will be required for a liquid at a low temperature.

327. The External Latent Heat Of Vaporization, L_E, is the *external-work heat* which must be added to the liquid to vaporize it or which is given up by the vapor when it is liquefied. It is the heat energy which must be expended in overcoming the resistance of external forces to the increase of volume of a liquid substance, which is incident to its vaporization. It is equivalent to the mechanical work done by the substance in expanding from the liquid state to the vapor condition of the gaseous state. See explanation below.

EXPLANATION.—Consider a cylinder (Fig. 316) which has an internal sectional area of 1 sq. ft. and which is somewhat over 26.8 ft. high. The cylinder stands open in the atmosphere—which imposes on it an absolute pressure of 14.7 lb. per sq. in. Suppose that 1 lb. of water at a temperature of 212° F. is placed in the cylinder, as at *I*. Now add heat and vaporize this 1 lb. of water. Experiment will show (see Steam Table 394 in Div. 11), that it will require 970.4 B t.u. (the latent heat of vaporization) to vaporize the 1 lb. of water at 212° F. into steam at 212° F. Now, the steam thus formed will, so experiment shows, force the air out of the cylinder *I* against the atmospheric pressure of 14.7 lb. per sq. in. (2,117 lb. per sq. ft.) and will exactly fill the cylinder—as in Fig. 316-*II*—which has a volume of 26.8 cu. ft.

The external work done, by the expansion of the water into steam, under atmospheric pressure, will be: *Force* × *Distance* 2,117 × 26.8 = 56,376 *ft.-lb.* Now, this external work done by the steam in expanding accounts for only a small part of the total latent heat of 970.4 B.t.u. which was expended in changing the liquid into a vapor. Thus: 56,736 *ft.-lb.* ÷ 778 = 72.8 *B.t.u. = external latent heat of vaporization.* The remainder: 970.4 − 72.8 = 897.6 *B.t.u. = internal latent heat of vaporization* and is heat which was expended in disgregation work.


P
14.7 Lb. Per Sq. In. Pressure
Piston Inserted
Pulley
2,117 Lb. W
Steam Forces Air Out Against 14.7 Lb. Per Sq. In. Pressure
1 Lb. Of Water
Cylinders All 1 Sq. Ft. Cross-Section
26.8 Ft.
Steam
Air All Expelled
Weightless Piston
Condensed Steam 26.8 Ft.
Weight Lifted By Energy of External Latent Heat Of Vaporization
Flame (Heat Being Added)

I-Water Being Vaporized II-Vaporization Completed III-Steam Re-Condensed

Fig. 316.—Showing external latent heat of vaporization converted into mechanical work.

The external work done by the vaporization might be recovered if, (Fig. 316-*II*) a tight piston *P* is inserted in the cylinder and the 1 lb. of steam be cooled so that it will contract (condense) back into 1 lb. of water at 212° F. as at *III*—Fig. 316. Then the atmospheric pressure would force *P* down, lifting *W*. *W*, which weighs 2,117 lb., would be lifted 26.8 ft., because 2,117 × 26.8 = 56,736 *ft.-lb.;* all friction losses are here neglected. Thus the external work done during the vaporization would be recovered. This is one of the principles the application of which renders useful a condenser (Sec. 513) on a steam engine or turbine.

328. When A Liquid Is Vaporized, The Latent Heat Of Vaporization Required Therefor Is Abstracted From Surrounding Objects.—Thus vaporization is, in reality, a cooling process. The heat thus required may be taken from the flame of a lamp (Fig. 307) or from the flame of a coal fire under a steam boiler. Or, as explained in preceding Sec. 300, the heat may be drawn from the liquid itself, thereby cooling the liquid. This principle is utilized practically in a number of useful ways, the most important of which have been mentioned in Sec. 293.

329. When A Vapor Condenses, Its Latent Heat Of Vaporization Is Given Up To Surrounding Objects.—Condensation is defined and discussed briefly in preceding Sec. 162. Thus, when 1 lb. of vapor is condensed due either to increased pressure or decreased temperature or both, it releases the number of B.t.u. (Sec. 322) which is equivalent to its latent heat of vaporization. With a given pressure, condensation takes place at the same temperature at which vaporization occurs.

Example.—The heat given out (Fig. 317) by a steam-heating system (Div. 17) is almost wholly heat which is released by the condensation of steam in the radiators and then transmitted through their walls to warm the air of the room.

Example.—In condensers for steam power plants and other services, the steam or vapor is condensed by cooling it, usually with cold water. The latent heat of vaporization thus released is absorbed by the cooling water and raises its temperature.

Example.—Closed tank *K* in Fig. 318 is of such size that it will contain exactly 1 lb. of steam at 0.0 lb. per sq. in. gage pressure—or 14.7 lb. per sq. in. absolute pressure. That is, it will contain 1 lb. of steam at atmospheric pressure. The tank is fitted with an automatic air-inlet valve, *B*, or vacuum aker beaker which opens to the atmosphere at the precise instant necessary to prevent formation of a partial vacuum by condensation of the steam. Thereby, the pressure within *K* is prevented from falling below 14.7 lb. per sq. in.

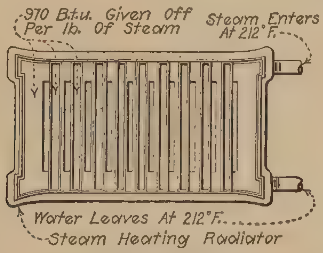


Fig. 317.—Showing heating with steam radiator through latent heat of vaporization.

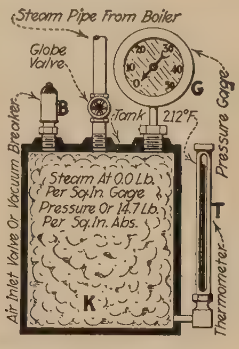

Steam Pipe From Boiler
Globe Valve
Air Inlet Valve Or Vacuum Breaker
B
G
Pressure Gage
Tank
212°F.
Steam At 0.0 Lb. Per Sq. In. Gage Pressure Or 14.7 Lb. Per Sq. In. Abs.
T
Thermometer
K

Fig. 318.—Condensing steam at a constant pressure.

Now, 1 lb. of steam is admitted to *K*. The temperature *T*, of this steam, as shown by the steam table, is 212° F. The steam begins to cool. It gives up heat to surrounding objects as indicated by *AB* in Fig. 319. Immediately some of the steam condenses to water at 212° F. But the temperature of the remaining steam stays constant, as indicated by line *AB*, until 970.4 B.t.u. has been given up: The latent heat of steam at atmospheric pressure is 970.4 B.t.u. The remainder of the steam condenses gradually. When exactly 970.4 B.t.u. have been given up, all of the steam will have condensed to water.

If heat be further abstracted from the water (*BC*, Fig. 319), its temperature will be decreased correspondingly. When 180 B.t.u. have been abstracted, the temperature of the water will then be 32° F. This condensation process is just the reverse of the vaporization process which is described in connection with Figs. 314 and 315.

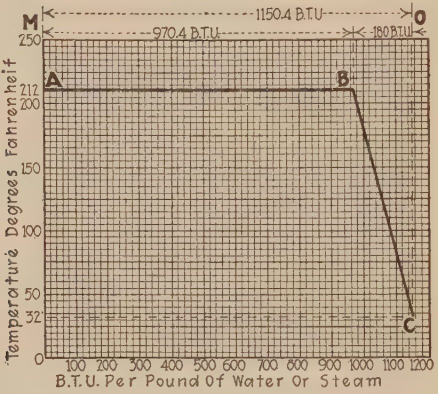


Fig. 319.—Illustrating latent-heat phenomenon in condensation of 1 lb. of steam.

330. Atmospheric Air Contains oxygen, nitrogen, a little carbon dioxide, traces of other rare gases, and *water vapor*. The air is, therefore, a mixture of gases and water vapor. The water vapor is in the air principally as the result of evaporation from the surfaces of rivers, lakes, ponds, and from "moist" objects. The water vapor in the air is not, usually, in the saturated state. That is, the air can usually be cooled or compressed somewhat before the moisture (water vapor) in it is condensed. The term *humidity* is used to describe the condition of air which contains water vapor; see following section.

331. Atmospheric Humidity may be expressed in two different ways: (1) *The absolute humidity* (Table 332) which expresses the total weight of water vapor in a unit volume of air. (2) *The relative humidity*, which expresses the ratio which exists between the weight of vapor actually present in a unit volume of air to the weight that would be present if the vapor were saturated at its actual temperature. This ratio is commonly denoted as a percentage of complete saturation.

332. Table Showing Absolute Humidities Or The Weights, In Grains Per Cubic Foot, Corresponding To Different Temperatures And Percentages Of Relative Humidity Of Aqueous Vapor In Atmospheric Air.

Air temperature, in deg. Fahr.	Percentage of relative humidity									
	10 %	20 %	30 %	40 %	50 %	60 %	70 %	80 %	90 %	100 %
−20	0.017	0.033	0.050	0.066	0.083	0.100	0.116	0.133	0.149	0.166
−10	0.028	0.057	0.086	0.114	0.142	0.171	0.200	0.228	0.256	0.285
0	0.048	0.096	0.144	0.192	0.240	0.289	0.337	0.385	0.433	0.481
10	0.078	0.155	0.233	0.310	0.388	0.466	0.543	0.621	0.698	0.776
20	0.124	0.247	0.370	0.494	0.618	0.741	0.864	0.988	1.112	1.235
30	0.194	0.387	0.580	0.774	0.968	1.161	1.354	1.548	1.742	1.935
40	0.285	0.570	0.855	1.140	1.424	1.709	1.994	2.279	2.564	2.849
50	0.408	0.815	1.223	1.630	2.038	2.446	2.853	3.261	3.668	4.076
60	0.574	1.149	1.724	2.298	2.872	3.447	4.022	4.596	5.170	5.745
70	0.798	1.596	2.394	3.192	3.990	4.788	5.586	6.384	7.182	7.980
80	1.093	2.187	3.280	4.374	5.467	6.560	7.654	8.747	9.841	10.934
90	1.479	2.958	4.437	5.916	7.395	8.874	10.353	11.832	13.311	14.790
100	1.977	3.953	5.930	7.906	9.883	11.860	13.836	15.813	17.789	19.766
110	2.611	5.222	7.834	10.445	13.056	15.667	18.278	20.890	23.501	26.112

NOTE.—The above table is an abstract from PSYCHROMETRIC TABLES by C. F. Marvin, published by the U. S. Weather Bureau, Washington, D. C., as Bulletin No. 235.

333. Humidity Of The Atmosphere is that condition of atmospheric air wherein it is more or less permeated with water vapor. Humidity is a universal and necessary attribute of the earths' atmosphere. Atmospheric air in one locality may be many times less humid—contain less water vapor—than in another. But nowhere will it be found entirely without water vapor. The humidity varies with the temperature. The cool air at the summit of a mountain is, generally, much less humid than the comparatively warm air in the valley at the mountain's base.

NOTE.—EXISTENCE OF A PROPER AMOUNT OF WATER VAPOR IN THE ATMOSPHERE IS ESSENTIAL to comfortable and hygienic living conditions, both for plants and animals. For human beings, too much humidity is about as uncomfortable as too little. When the humidity is too low, one experiences a dry parched feeling. When it is too great, the "sticky" sensation, which occurs on damp hot days, is felt. In winter when the natural humidity within buildings is low due to the low humidity out of doors and the drying effect of the heating systems, the deficiency may be supplied (Fig. 320) by a *humidifier*. In certain manufacturing processes a definite humidity is quite necessary. A suitably-designed humidifier will provide it. In other processes, for which dry air is required, the moisture may be removed by a *dehumidifier*, or *air drier* (Fig. 321).

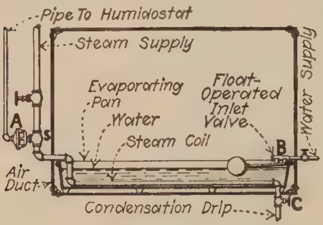


FIG. 320.

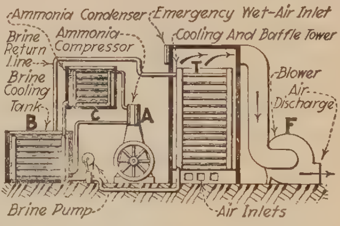


FIG. 321.

FIG. 320.—Cross section showing humidifying apparatus, or "humidifier," in air duct of ventilating system. (When the humidity becomes low, the humidostat, which is located in a room above, admits air pressure to diaphragm-valve *A*, thus opening steam valve, *S*.)

FIG. 321.—Elementary air drier for blast furnace. (Ammonia is compressed in *A*, condensed in *C*, and allowed to expand into *B*. Brine is circulated through *B* and *T*. Air is sucked by *F* through *T*, wherein it is cooled below the dew point, and the condensed vapor is removed, as water, by baffles.)

334. Relative Humidities May Be Determined By Means Of The Sling Psychrometer (Fig. 322) or wet-and-dry-bulb thermometer. The utility of this instrument is based upon the principle (Sec. 300) of cooling by evaporation. Evaporation of moisture from the muslin cloth which envelopes the bulb of thermometer *A* produces a cooling effect thereof which causes thermometer *A* to give a lower reading than thermometer *B*, the bulb of which is exposed directly to the air.

EXPLANATION.—The muslin which envelopes the wet bulb (Fig. 322) is thoroughly saturated with water. The sling psychrometer is then whirled rapidly through the air for about one minute. This is to insure a rapid penetration of air among the fibers of the cloth around the wet bulb.

The difference between the indications of thermometers *A* and *B* is then noted. The one with the wet bulb will, generally, show a lower reading than the one with the dry bulb. This is due to the fact that, in general, the vapor in atmospheric air is not saturated. When there is no difference between the readings of thermometers *A* and *B*, the water vapor which is intermingled with the air is fully saturated.

The psychrometer is based on the law of evaporation (Sec. 298) that the rate of evaporation is greater into dry air than into air which contains vapor. The whirling of the thermometers causes the water on the wet bulb to evaporate rapidly. The evaporation cools (Sec. 300) the thermometer and the water around its bulb. Evaporation and cooling continue until the water is cooled to the temperature at which its vapor pressure is just sufficient to keep driving off vapor molecules at a constant rate.

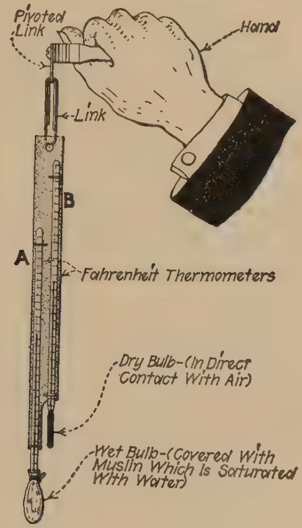

Pivoted Link
Hand
Link
B
A
Fahrenheit Thermometers
Dry Bulb-(In Direct Contact With Air)
Wet Bulb-(Covered With Muslin Which Is Saturated With Water)

Fig. 322.—A sling psychrometer.

Now it can be shown that the relative humidity of the air is a function of the temperature-difference indicated by the wet- and dry-bulb thermometers of a sling psychrometer. Hence, when the temperature-differences are known, the corresponding relative humidities may be determined by consulting Table 335.

Example.—Suppose that air at a temperature of 70° F. is drawn into a building through the ventilating ducts. Also, suppose that a humidity test, made with a sling psychrometer (Fig. 322), shows a temperature difference, between thermometers *A* and *B*, of 17° F. Then, by Table 335, the relative humidity is 30 *per cent.* This value is found in the same horizontal row with 70, which is the given air-temperature, and in the same vertical row with 17, which is the given psychrometer-difference.

335. Table Showing Relative Humidities, In Per Cent., Corresponding To Various Wet- And Dry-bulb Temperature Differences (accurate for an atmospheric pressure of 14.25 lb. per sq. in. = 29-in. barometer).

Air temperature, in deg. Fahr.	Temperature-difference, in degrees Fahrenheit, between wet- and dry-bulb thermometers																				
	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
32	100	90	79	69	60	50	41	31	22	13	4										
34	100	90	81	72	62	53	44	35	27	18	9	1									
36	100	91	82	73	65	56	48	39	31	23	14	6	0								
38	100	91	83	75	67	59	51	43	35	27	19	12	4								
40	**100**	**92**	**84**	**76**	**68**	**61**	**53**	**46**	**38**	**31**	**23**	**16**	**9**	**2**							
42	100	92	85	77	70	62	55	48	41	34	28	21	14	7	0						
44	100	93	85	78	71	64	57	51	44	37	31	24	18	12	5	0					
46	100	93	86	79	72	65	59	53	46	40	34	28	22	16	10	4	0				
48	100	93	87	80	73	67	60	54	48	42	36	31	25	19	14	8	3	0			
50	**100**	**93**	**87**	**81**	**74**	**68**	**62**	**56**	**50**	**44**	**39**	**33**	**28**	**22**	**17**	**12**	**7**	**2**	**0**		
52	100	94	88	81	75	69	63	58	52	46	41	36	30	25	20	15	10	6	0	0	
54	100	94	88	82	76	70	65	59	54	48	43	38	33	28	23	18	14	9	5	0	0
56	100	94	88	82	77	71	66	61	55	50	45	40	35	31	26	21	17	12	8	4	0
58	100	94	89	83	77	72	67	62	57	52	47	42	38	33	28	24	20	15	11	7	3
60	**100**	**94**	**89**	**84**	**78**	**73**	**68**	**63**	**58**	**53**	**49**	**44**	**40**	**35**	**31**	**27**	**22**	**18**	**14**	**10**	**6**
62	100	94	89	84	79	74	69	64	60	55	50	46	41	37	33	29	25	21	17	13	9
64	100	95	90	85	79	75	70	66	61	56	52	48	43	39	35	31	27	23	20	16	12
66	100	95	90	85	80	76	71	66	62	58	53	49	45	41	37	33	29	26	22	18	15
68	100	95	90	85	81	76	72	67	63	59	55	51	47	43	39	35	31	28	24	21	17
70	**100**	**95**	**90**	**86**	**81**	**77**	**72**	**68**	**64**	**60**	**56**	**52**	**48**	**44**	**40**	**37**	**33**	**30**	**26**	**23**	**20**
72	100	95	91	86	82	78	73	69	65	61	57	53	49	46	42	39	35	32	28	25	22
74	100	95	91	86	82	78	74	70	66	62	58	54	51	47	44	40	37	34	30	27	24
76	100	96	91	87	83	78	74	70	67	63	59	55	52	48	45	42	38	35	32	29	26
78	100	96	91	87	83	79	75	71	67	64	60	57	53	50	46	43	40	37	34	31	28
80	**100**	**96**	**91**	**87**	**83**	**79**	**76**	**72**	**68**	**64**	**61**	**57**	**54**	**51**	**47**	**44**	**41**	**38**	**35**	**32**	**29**
82	100	96	92	88	84	80	76	72	69	65	62	58	55	52	49	46	43	40	37	34	31
84	100	96	92	88	84	80	77	73	70	66	63	59	56	53	50	47	44	41	38	35	32
86	100	96	92	88	85	81	77	74	70	67	63	60	57	54	51	48	45	42	39	37	34
88	100	96	92	88	85	81	78	74	71	67	64	61	58	55	52	49	46	43	41	38	35
90	**100**	**96**	**92**	**89**	**85**	**81**	**78**	**73**	**71**	**68**	**65**	**62**	**59**	**56**	**53**	**50**	**47**	**44**	**42**	**39**	**37**
92	100	96	92	89	85	82	78	75	72	69	65	62	59	57	54	51	48	45	43	40	38
94	100	96	93	89	86	82	79	75	72	69	66	63	60	57	54	52	49	46	44	41	39
96	100	96	93	89	86	82	79	76	73	70	67	64	61	58	55	53	50	47	45	42	40
98	100	96	93	89	86	83	79	76	73	70	67	64	61	59	56	53	51	48	46	43	41
100	**100**	**96**	**93**	**90**	**86**	**83**	**80**	**77**	**74**	**71**	**68**	**65**	**62**	**59**	**57**	**54**	**52**	**49**	**47**	**44**	**42**
102	100	96	93	90	86	83	80	77	74	71	68	65	63	60	57	55	52	50	47	45	43
104	100	97	93	90	87	84	80	77	74	72	69	66	63	61	58	56	53	51	48	46	44
106	100	97	94	90	87	84	81	78	75	72	69	66	64	61	59	56	54	51	49	47	45

NOTE.—THE ABOVE TABLE IS AN ABSTRACT FROM PSYCHROMETRIC TABLES by C. F. Marvin, published by the U. S. Weather Bureau, Washington, D. C., as Bulletin No. 235.

336. Relative-humidity Determinations Are Of Much Practical Importance.—Forecasts of probable rain or frost are based by weather-bureau experts on relative-humidity observations. In many greenhouses the humidity is measured regularly. It is then systematically maintained at such values that the plants will thrive. In industrial, office, amusement, hospital, and residence buildings measurement and control of humidity may be desirable or necessary. In such buildings, the relative humidity should be about 50 to 60 per cent. In certain industrial operations lower or higher relative humidities are frequently necessary and are maintained.

337. Low Relative Humidity In Inhabitated Buildings Causes Colds And Wastes Fuel.—"Dry" air affects the respiratory organs adversely. Also, when the air is "dry" the evaporation of perspiration is rapid. The skin is cooled accordingly. Hence, with two rooms at the same temperature, a person will feel much warmer in the one wherein the humidity is high than in the one in which it is low. The fuel waste thus due to low interior humidities is estimated to be from 12 to 25 per cent.

NOTE.—MILLIKAN AND GALE STATE that "The average home that is heated to 72° F. by steam or hot water is estimated by health authorities to have a relative humidity of 30 per cent. With hot-air heating, it may be 25 per cent. This is less than the average humidity of extensive desert regions.

338. A Psychrometric Chart (Fig. 323) provides a means for determining graphically the relative and absolute humidities of atmospheric air and for solving many problems is *air conditioning*—that is, in regulating the temperature and humidity of the air.

EXAMPLE.—If, in a room, the wet-bulb and dry-bulb temperatures are, respectively, 74 and 85° F., what are the relative and absolute humidities? SOLUTION.—Following vertically upward from the dry-bulb temperature of 85° F. to the inclined line representing a wet-bulb temperature of 74° F. the relative humidity is found to be 60 *per cent.* Also, following upward from 85° F., mark on the lower scale to the curve F and then horizontally to the left to the scale F, it is found that saturated water vapor at 85° F. weighs 12.7 *grains per cu. ft.* Hence, the water vapor in air of 60 per cent. relative humidity at 85° F. will weigh: $0.60 \times 12.7 = 7.6$ *grains per cu. ft.*

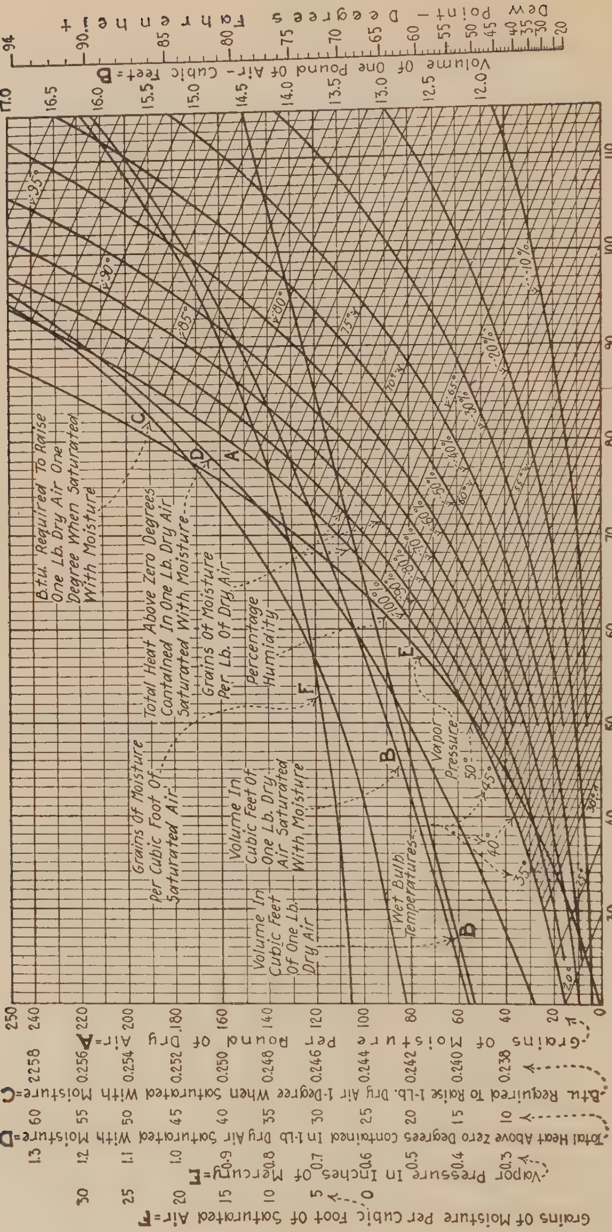


FIG. 323.—See following page for explanation.

339. Dew, Rain, Hail, Frost, Sleet, Snow, Fog, And Clouds Are All The Result Of Condensation Of Moisture In The Atmosphere (the moisture or aqueous vapor is that produced by evaporation, Sec. 296). Which of these phenomena results is, as will be described, determined by the specific conditions under which the condensation occurs.

340. The Dew Point is the temperature at which the water vapor in the atmosphere becomes saturated (Sec. 305) and will condense or deposit as drops of water or dew.

Note.—The Dew Point Will Be Different For Different Absolute Humidities.—The greater the humidity the higher the dew point. The *relative* humidity at the dew point is always 100 per cent. As the temperature of atmosphere at 100 per cent. relative humidity decreases, there will be a certain condensation—production of dew—for each degree temperature decrease. But even if the air temperature is decreased to 32° F.—the freezing point of water—some moisture will remain in the air.

341. Dew is formed when—at night—the temperature of a thin layer of atmosphere, which lies close to the earth's surface, falls to the dew point. After the sun sets, the earth's surface and the objects on it lose heat by radiation. Thereby they are cooled to a temperature lower than that of the main body of the atmosphere, which cools more slowly. But the temperature of the relatively thin stratum of atmosphere (air and water vapor) immediately adjacent to the cooled earth's surface and to the objects on it—such as plants, stones, and earth—is reduced to the dew-point or somewhat below. Thereby dew is formed and deposited on the objects.

Note.—"Sweating" Occurs When Water Vapor Condenses on a cool surface which has reduced the temperature of the vapor to the dew point. Examples are the sweating of cold-water pipes in a warm

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Fig. 323.—Psychrometric chart (Barometric pressure—29.92 in. mercury column—reproduced by permission from the Carrier Engineering Corporation, Newark, N. J.) All temperatures are in degrees Fahrenheit. *Dry bulb temperatures* are represented by vertical lines with values indicated on lower edge of chart. *Wet bulb temperatures* are represented by oblique straight lines with values indicated on the lines. *Dew point temperatures* are represented by horizontal lines and their values indicated at the right. *Percentages of relative humidity* are represented by converging curved lines with values indicated between the oblique straight lines for 63° and 64° wet bulb temperature. *Any two of the above properties may be found if the other two are known.* First, find the point of intersection of the lines representing the given properties, and then follow through this point, the lines representing the unknown properties, and the values of the latter can be read from their respective scales.

humid room and that of the inner surfaces of window panes when it is warm and humid inside and cold outside. Essentially, *sweating is a dew formation. Sweating can be prevented* by causing a rapid circulation of air about the surface upon sweating tends to occur—the removal of the air (and vapor) from the cold surface is thus effected before its temperature has a chance to be cooled to the dew point. Sweating may also be prevented by covering the surface which tends to "sweat" with a heat-insulating (Sec. 114) material. This heat insulator will prevent the rapid transfer of heat from the warm vapor to the cool surface and thus minimize sweating.

342. Frost is formed if the condensation, as described under "dew," occurs upon a surface the temperature of which is lower than the freezing point of water. Windows become "frosted" in winter, when the outside temperature is considerably below the freezing point of water. It may be prevented just as is sweating (see preceding note).

343. Fog results if the cooling effect of the earth's surface (see "dew" above) is sufficient to decrease to the dew point the temperature of a rather thick stratum of atmosphere which lies adjacent to the earth. The water vapor in the atmosphere then condenses on the dust particles which are suspended therein and forms a fog.

344. Clouds result when, at a considerable distance above the earth's surface, the temperature of a body of water vapor in the atmosphere is decreased to the dew point. This may occur when a current of warm air passes into a cold upper region: The water vapor condenses around suspended dust particles and forms clouds.

NOTE.—RAIN is formed (Millikan and Gale) if the cooling is sufficient to free a considerable amount of moisture. Then the drops become large and fall. If this falling rain freezes before it reaches the ground, it is called *sleet*. If the temperature at which condensation begins is below freezing, the condensing moisture forms into *snowflakes* (Fig. 324). When the violent air currents which accompany thunder-storms carry the condensed moisture up and down several times through alternate regions of snow and rain, *hailstones* are formed.

345. Distillation is the process of separating the more volatile parts of a substance, from those less volatile, by vaporizing and subsequently condensing. For a liquid, it is done (Fig. 325) by first boiling the solution, B, and then condensing the resulting vapor in a separate vessel, C. By this means a liquid may be freed from whatever solid substances (which do not vaporize at all) it may hold in solution. Or it may be freed from those liquid substances which vaporize at different temperatures (see fractional distillation, Sec. 346).

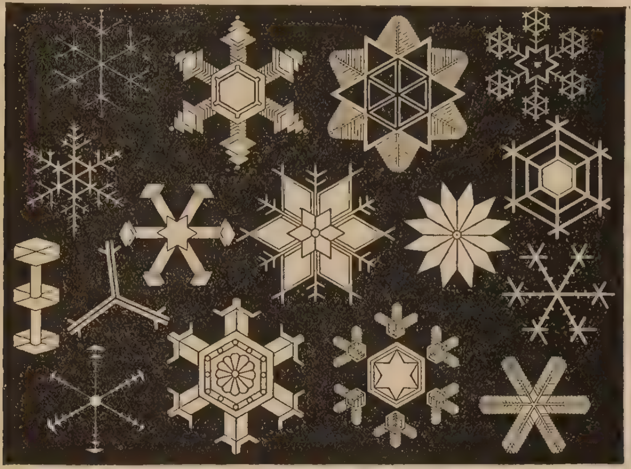


Fig. 324.—Snow-flake crystals.

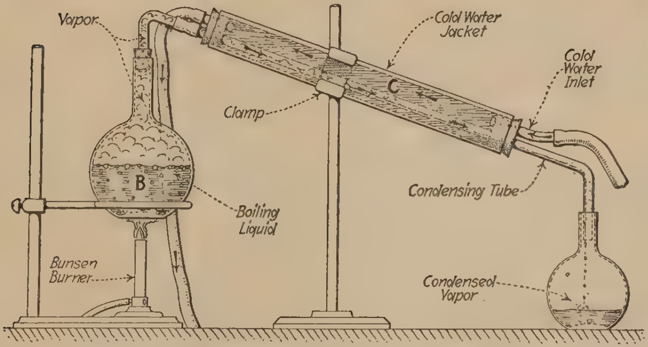


Fig. 325.—Illustrating the principle of distillation.

Example.—The water which is fed to a steam boiler usually holds mineral substances in solution. The water is vaporized by boiling. It is thus freed from the mineral substances. The water, in the form of steam, is conveyed from the boiler. The mineral substances, in the form of *scale* (Sec. 174), remain behind. The steam may be condensed in the radiators of a heating system. Then, provided there were no gaseous, nor highly volatile liquid, substances in the solution which was fed to the boiler, pure water will be drained from the radiators. Thus the process of distillation will be completed.

Note.—When Brine Or Salt-water Is Boiled, The Resulting Steam Contains No Salt.—Similarly, with many other liquid solutions, the vapor arising from the solution is free from the solid substances which were dissolved in the liquid.

346. Fractional Distillation is the process of separating different liquid substances which have different boiling temperatures, from one another. When both or several of the liquid constituents of a solution are volatile, the vapors of both or of all will each issue from the solution at its boiling temperature. (The boiling temperature of a solution of two or more liquids usually lies between the highest and the lowest boiling temperatures of any of the component liquids although it sometimes lies below that of either constituent.) But, the liquid which has the lower boiling temperature will supply most of the vapor. Hence by a prolonged distillation at gradually increasing temperatures different volatile liquids may usually be separated from the same solution.

Explanation.—The liquid which has the lower boiling point will predominate in the ensuing vapor. Thus, its concentration in the remaining liquid will gradually decrease and the remaining liquid in the boiler will gradually assume a higher boiling point. The first vapor that comes off will, when condensed, provide a solution which has a greater concentration of the more volatile liquid, than had the original solution. As the boiling point increases, less and less of the more volatile liquid is evaporated and condensed. Finally, a point is reached where the composition of the condensing vapor (if but two liquids were present in the original solution) becomes about the same as that of the original solution. At this point the distillation is either stopped or the distillate (condensed vapor) is led into a different vessel than was used up to this point. If a greater concentration of the more volatile liquid (than the first distillation provides) is desired, the first distillate is again subjected to a second distillation. In this way, by successive distillations, a product of almost any desired concentration may be effected.

Example.—Fractional Distillation Of Crude Oil Provides The Various Petroleum Products (Fig. 326) such as naphtha, benzine, gasoline, kerosene, and the lubricating oils. The crude oil is first heated to a relatively low temperature which vaporizes the more-volatile products. These are condensed. The boiling point of the liquid which remains in the still gradually rises as these more volatile products are driven off as vapors. At a certain temperature, the distillate is piped to a second receiver. Here the components of the next less volatility are collected. As the boiling point reaches a certain second value, the distillate is led to a third receiver and so on until all of the "fractions" have been separated. Each of these products or fractions is still a mixture but each is composed mainly of compounds all having nearly the same boiling point. Some of the products are petroleum ether, gasoline, naphtha, benzine, kerosene, and heavier oils. At some stage, the residual oil is chilled and then crystallizes partly into flakes (either paraffin or asphalt) which, except for the filtration of paraffin, are not further treated. Certain crude oils give a paraffin residue and others an asphalt residue.

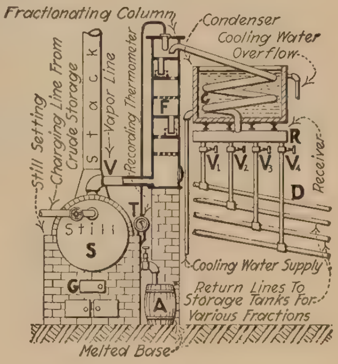


FIG. 326.—Elementary petroleum still. (Crude oil is charged into *S*, and heated by coke fire fed at *G*. The vapor rises through *V* into *F*. In this *fractionating column*, *F*, the vapors of the liquids of the higher boiling temperatures (which unavoidably are vaporized and pass over with the liquids of the lower boiling temperature) are partially condensed. The partially condensed liquids are then, in *F*, intercepted by the baffles and thereby caused to flow back into the still —instead of passing over into the condenser with the more volatile vapors. The vapors are condensed in *C* and flow into *R*. The various fractions are separated by valves, V_1, V_2, etc. according to temperature indicated by *T*. The distillate is run off through pipes *D*. The hot base—asphalt, etc.—is allowed to solidify in barrels at *A*.)

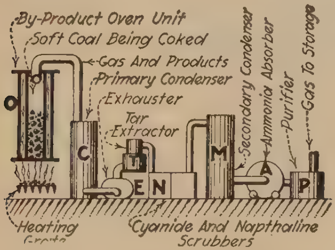


FIG. 327.—Diagram of elementary by-product coke plant. (The gas and other products given off by the coking operation in *O* are drawn, by *E*, through *C*. Tar is removed in *T* and naphthaline and cyanides in *N*. Ammonia is removed in *A* after cooling in *M* and the gas goes through *P* to storage holder.)

347. Destruction Distillation is distillation of the volatile components of solid substances, as *wood*, *coal*, *bone*. It results from a process of decomposition (Sec. 155). The substances are decomposed (Fig. 327) in closed vessels, by application of heat. The volatile ingredients are thus vaporized. The vapors resulting from different temperatures are conveyed to separate vessels wherein they are condensed. The non-volatile ingredients remain in the heating vessel as a semi-liquid or solid residuum.

348. All Gases May Be Liquefied If Subjected To Sufficiently Low Temperature And High Pressure.—If any vapor be compressed until its pressure is equal to its saturation pressure at the then existing temperature, the vapor will be condensed—that is, it will be liquefied. Again, if the temperature of a vapor be decreased until its temperature equals the saturation temperature at the then-existing pressure, the vapor will be liquefied. Or the pressure may be increased and the temperature decreased simultaneously until saturation and consequent liquefaction occurs. There is, however, a certain temperature for every vapor, above which it cannot be liquefied (Sec. 349). Since (Sec. 225) every gas is, at certain temperatures, a vapor, these same laws hold for all gases.

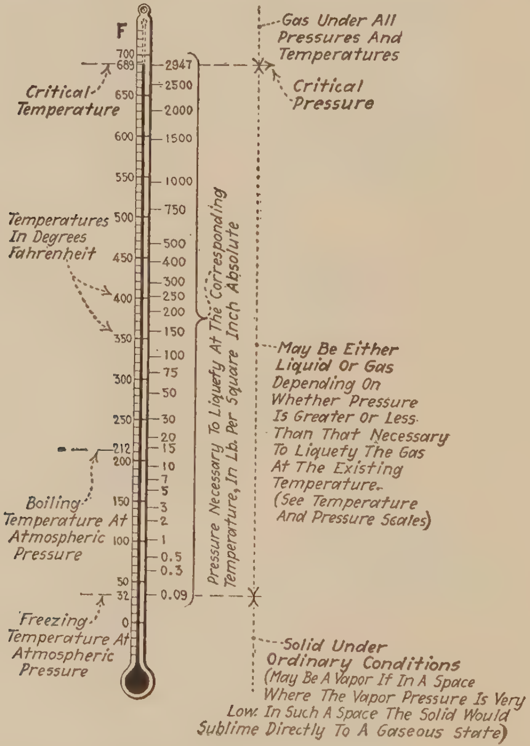

F
700
689
650
600
550
500
450
400
350
300
250
212
200
150
100
50
32
0
2947
2500
2000
1500
1000
750
500
400
300
250
200
150
100
75
50
30
20
15
10
7
5
3
2
1
0.5
0.3
0.09
Critical Temperature
Temperatures In Degrees Fahrenheit
Boiling Temperature At Atmospheric Pressure
Freezing Temperature At Atmospheric Pressure
Pressure Necessary To Liquefy At The Corresponding Temperature, In Lb. Per Square Inch Absolute
Gas Under All Pressures And Temperatures
Critical Pressure
May Be Either Liquid Or Gas Depending On Whether Pressure Is Greater Or Less Than That Necessary To Liquefy The Gas At The Existing Temperature. (See Temperature And Pressure Scales)
Solid Under Ordinary Conditions (May Be A Vapor If In A Space Where The Vapor Pressure Is Very Low. In Such A Space The Solid Would Sublime Directly To A Gaseous State)

FIG. 328.—Illustrating the critical conditions for water. (According to the later steam tables, the critical temperature and pressure for water are 706.1°F. and 3,200 lb. per sq. in. abs.)

NOTE.—A PERMANENT GAS was defined by Faraday as one which resisted liquefaction. Since he liquefied all known gases except hydrogen, nitrogen, oxygen, carbon monoxide and methane, these five were formerly called the permanent gases. But since then, all known gases have been liquefied. Hence, strictly speaking, there is no such thing as a permanent gas. Sometimes the term is loosely and incorrectly used to designate gases (such as the five mentioned above) which can only be liquefied at extremely low temperatures.

349. The Critical Temperature Of A Substance is that temperature above which it cannot exist as a liquid (Figs. 328 and 329). There is a certain critical temperature for each element and compound; see Table 350. Above its critical temperature, no pressure (regardless of how great it is) will liquefy a substance. The pressure of a saturated vapor (Sec. 308) at its critical temperature is called its *critical pressure*. Hence, its critical pressure is the lowest pressure at which a substance

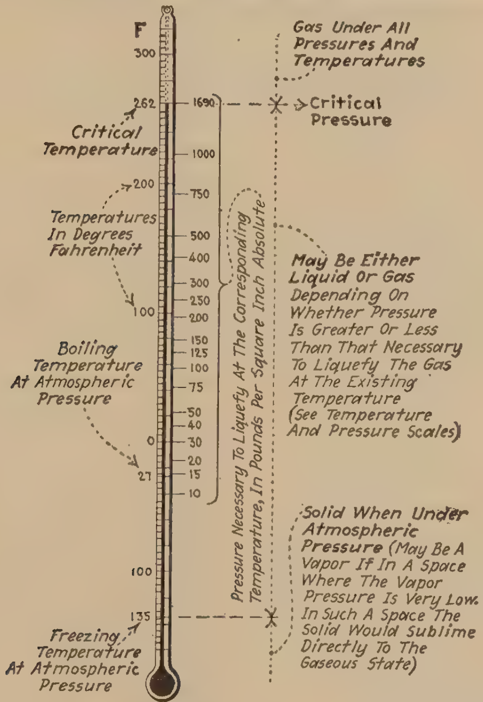

F
300
262
Critical Temperature
200
Temperatures In Degrees Fahrenheit
100
Boiling Temperature At Atmospheric Pressure
0
27
100
135
Freezing Temperature At Atmospheric Pressure
1690
1000
750
500
400
300
250
200
150
125
100
75
50
40
30
20
15
10
Pressure Necessary To Liquefy At The Corresponding Temperature, In Pounds Per Square Inch Absolute
Gas Under All Pressures And Temperatures
Critical Pressure
May Be Either Liquid Or Gas Depending On Whether Pressure Is Greater Or Less Than That Necessary To Liquefy The Gas At The Existing Temperature (See Temperature And Pressure Scales)
Solid When Under Atmospheric Pressure (May Be A Vapor If In A Space Where The Vapor Pressure Is Very Low. In Such A Space The Solid Would Sublime Directly To The Gaseous State)

FIG. 329.—Illustrating the critical conditions for ammonia.

can exist in the liquid state when it is at its critical temperature. The *critical density* of a substance is its density at its critical temperature and critical pressure. The critical density of a substance is the same whether it is in the liquid or gaseous state.

Note.—The Critical Temperature Of A Substance may also be defined as that temperature above which the substance, when in its gaseous state, cannot be liquefied by pressure alone. Below its critical temperature the substance can be liquefied by pressure only.

Note.—Existence of any two of the three critical conditions: pressure, temperature, and density is contingent on the simultaneous existence of the third.

Examples.—There can be no such thing as liquid air above its critical temperature which is −220° F. (220 degrees below zero). There can be no such thing as liquid water above the critical temperature of steam which is 706° F. (Table 394).

Example.—If it is desired to change the state (Sec. 49) of gaseous air to liquid air, the first step is to subject it to a pressure of about (see Table 350) 585 lb. per sq. in. abs. Next, while the air is subjected to this pressure, it must be cooled to somewhat below its critical temperature of −220° F. Then it will be converted into liquid air. If its temperature exceeds −220° F., no pressure, however great, will liquefy it. If the temperature is less than −220° F., a pressure correspondingly less than 585 lb. per sq. in. abs. will cause liquefication.

Example.—Consider a quantity of water which is confined in a closed vessel. The vessel is heated. Thereby some of the water is vaporized. As additional heat is imparted and more of the water vaporized, the pressure within the vessel increases. This increases the density of the vapor. But as the temperature rises, the density of the water diminishes (Sec. 205). Ultimately a temperature and pressure will be reached at which the density of the steam will be equal to that of the water. This temperature and pressure are, approximately, 706° F. and 3,200 lb. per sq. in. abs. (Marks and Davis' Steam Tables). When this condition has developed, any further addition of heat will change all the water into steam since the water has then no latent heat of vaporization. A slight loss in heat will then result in instantaneous condensation of a considerable quantity of water.

Example.—If approximately equal volumes of liquid carbon dioxide and its saturated vapor are sealed (Fig. 330) in a heavy-walled glass tube, it may be easily heated above the critical temperature of carbon dioxide (88° F.) in warm water. As the temperature of the water approaches 88° F., the meniscus, *A*, or dividing line between the liquid and the vapor will give way to a foggy appearance at the point, *B*. At the instant that the critical temperature is passed, the tube will be full of gas only and will appear to be empty.

Note.—The Ease With Which The Critical Temperature Of A Gas May Be Attained Largely Determines The Facility With Which The Gas May Be Liquefied.—The vapors of many substances such as: water, alcohol, ether, ammonia, and carbon dioxide may be readily liquefied since temperatures (Table 350) well below their critical temperatures can readily be obtained. But liquefaction of certain gaseous substances such as air, carbon monoxide, and hydrogen is accomplished only with considerable difficulty. The reason is that the critical temperatures of these gases are (Table 350) extremely low and therefore difficult to obtain.

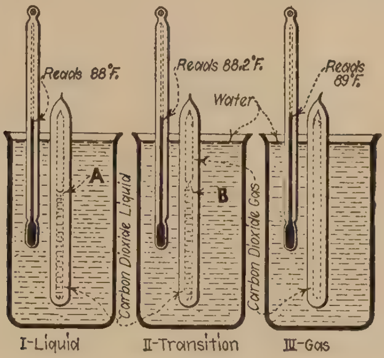


Fig. 330.—Showing vaporization of carbon dioxide at critical temperature and pressure.

350. Table Showing Critical Temperatures and Pressures Of Various Substances. (From Marks' MECHANICAL ENGINEERS' HANDBOOK.)

Substance	Critical temperature, deg. Fahr.	Critical pressure		Boiling temperature of liquid at atmospheric pressure, deg. Fahr.
		[1] In atmospheres	In lb. per sq. in.	
Acetylene (C_2H_2)	95.0	68.0	1,000	−117.4
Air	−220.0	39.0	573	
Alcohol (C_2H_6O)	421.0	65.0	956	172.4
Ammonia (NH_3)	266.0	115.0	1,691	− 27.4
Benzol (C_6H_6)	554.0	50.0	735	176.0
Bromine	512.0	....	.....	142.0
Carbon dioxide	88.2	77.0	1,132	−110.0
Carbon monoxide	−222.0	35.9	528	−310.0
Carbon disulphide	468.0	78.1	1,148	115.0
Chloroform	500.0	54.9	807	141.0
Chlorine	289.0	92.0	1,352	− 27.4
Ether ($C_4H_{10}O$)	381.2	37.0	544	95.0
Ethane	31.0	45.2	665	−135.0
Ethylene	50.0	54.0	794	−157.0
Helium	−448.6	3.0	44.1	−450.4
Hydrogen	−402.0	20.0	294	−423.0
Hydrogen chloride	125.6	87.0	1,278	−112.0
Hydrogen sulphide	212.0	94.0	1,382	− 61.6
Methane (CH_4)	−115.6	57.0	838	−263.0
Nitric oxide (NO)	−137.2	73.0	1,073	−238.0
Nitrous oxide (N_2O)	96.8	80.0	1,175	−134.0
Nitrogen	−236.0	35.0	514	−321.0
Oxygen	−180.4	50.0	735	−297.0
Pentane	386.6	34.0	500	96.8
Sulphur dioxide	314.6	80.0	1,175	14.0
[2] Water	706.1	217.8	3,200	212.0

[1] 1 atmosphere = 14.7 lb. per sq. in.

[2] From Marks and Davis' STEAM TABLES.

QUESTIONS ON DIVISION 10

1. Define *vaporization.* Give some examples of its practical applications.

2. Explain in general terms the distinction between a gas and a vapor.

3. What kind of a vapor is steam?

4. Name and define the three different kinds of vaporization.

5. Under what temperature conditions will evaporation occur?

6. Explain the molecular theory of evaporation.

7. State the laws governing evaporation. Explain each law.

8. What effect does evaporation have on the temperature of the evaporating liquid and the adjacent bodies? Explain. Give two commercial applications.

9. Give some examples of freezing and cooling by evaporation.

10. What is condensation? Explain. Give a practical application of heating by condensation.

11. What change in volume takes place when a substance vaporizes or condenses?

12. What is a saturated vapor? Explain saturation theoretically. What happens if a saturated vapor is cooled at a given pressure?

13. What are Dalton's laws for vapors? Explain an exception to the second law.

14. What determines the vapor pressure of a given liquid? What effect has the presence of another gas on evaporation? On vapor pressure?

15. What is meant by saturation pressure?

16. Why do bubbles form when a liquid is heated to its boiling point? Of what are they composed? Why do they sometimes disappear before they reach the liquid surface.

17. Why is ebullition usually more rapid than evaporation?

18. What is the relation between vapor pressure and boiling point? Illustrate with a sketch showing the forces which act upon a bubble.

19. Why does not a body of liquid all evaporate at once when heat is applied to it at its boiling point?

20. How does difference in pressure affect boiling point? Describe an experiment in which boiling point is lowered by a pressure change. One in which it is raised.

21. How is the boiling point of a liquid affected by a dissolved solid? By a dissolved gas?

22. Give two examples of sublimation.

23. What is latent heat of vaporization? Into what two parts may it be divided? Explain.

24. Why is the large latent heat of vaporization of water a disadvantage in steam power generation? An advantage in steam heating?

25. How does increased pressure and temperature affect latent heat of vaporization?

26. What are the principal constituents of atmospheric air?

27. Define *humidity.* In what two ways may the atmospheric humidity be expressed numerically?

28. What degree of humidity is most suitable for animal life? How may the humidity be increased artificially? How decreased?

29. Explain the principle and use of the psychrometer in determining relative humidity. What is the practical use of such determinations?

30. What is meant by *dew point?* How is dew formed?

31. Explain the *sweating* of cold objects in warm air. How may it be prevented? Give 2 ways.

32. Explain frost, fog, and rain? How is snow formed?

33. Explain fractional distillation. Destructive distillation. Give a commercial application of each.

34. What is the critical temperature of a substance? What is its critical pressure? Critical density? Describe condensation and vaporization at critical temperature and pressure.

35. What is the effect of the critical temperature of a gas on the ease with which it can be liquefied?

PROBLEMS ON DIVISION 10

1. How much heat must be added to 1 lb. of water at 32° F. to change it to steam at atmospheric pressure?

2. How much heat must be added to 1 lb. of ice at 32° F. to change it to steam at atmospheric pressure?

3. What is the weight of the water vapor in 1 cu. ft. of air at a temperature of 70° F., if the relative humidity is 55 per cent.?

4. The temperature of the wet- and dry-bulb thermometers in a room are 70° F. and 53° F. respectively. What is the relative humidity and what weight of water vapor does each cubic foot of air contain? Compute from the tables.

5. In an industrial plant, the wet- and dry-bulb temperatures are respectively 90° F. and 75° F. on a summer day. Find, by means of the psychrometric chart of Fig. 323, the relative humidity and the weight of water vapor in 1 cu. ft. of the air.

6. If, in the plant of Prob. 5, a relative humidity of 80 per cent. is necessary for certain processes, find what the wet-bulb thermometer should be made to read and how much moisture must be added to each cubic foot of air.

7. If, in Prob. 6, it is desired to raise the relative humidity by cooling the air, to what temperature must it be cooled?

8. (*a*) What is the state of water at the temperature of 800° F. and under the pressure of 200 lb. per sq. in. abs.? (*b*) At 800° F. and 3,500 lb. per sq. in abs.? (*c*) At 1,000 lb. per. sq. in. abs. and 500° F.? (*d*) At 350° F. and 75 lb. per sq. in. abs.?

9. (*a*) What is the state of ammonia at 70° F. and 100 lb. per sq. in. abs.? (*b*) At 700° F. and 500 lb. per sq. in. abs.? (*c*) At 140° F. and 500 lb. per sq. in. abs.? (*d*) At 0° F. and atmospheric pressure?

DIVISION 11

STEAM AND OTHER VAPORS

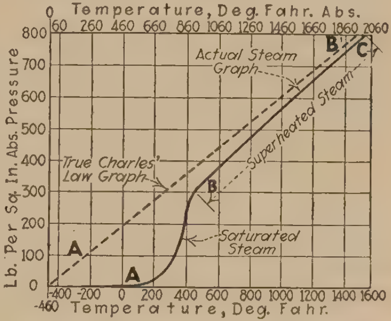


FIG. 331.—Showing deviation, of relation of temperature to pressure of steam, from Charles' law. Graph *ABC* shows the actual behavior of—water vapor—steam. (The values are for 1 lb. of steam confined to a constant volume of 1.62 cu. ft. If steam were a perfect gas, the graph would take the form of the dotted line *A'B'*.)

351. A Vapor Is Any Substance In The Gaseous State Which Does Not Even Approximately Follow The General Gas Law (Figs. 331 and 332). That is, as explained in Sec. 225, vapors are substances in the gaseous state at or near their liquefaction conditions. The general gas law is explained in Sec. 248. The reason for this departure of the performance of vapors from the general gas law is that the vapors, when heated or cooled, experience some disgregation work (Sec. 98). The general gas law is based on a perfect gas which would experience no disgregation work when heated or cooled (Sec. 258). But all known actual gases do experience small amounts of disgregation work. Vapors experience large amounts of disgregation work; this is very evident at the boiling point of a liquid at which point the liquid is changed to a vapor and a great change of volume occurs with no change in the

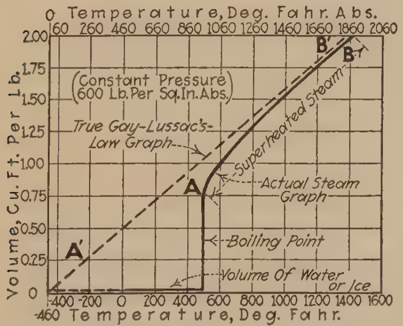


FIG. 332.—Showing deviation of water vapor—steam—from Gay Lussac's law at 600 lb. per sq. in. abs. pressure.

pressure which is exerted by the vapor or in its temperature. The consequence is that, for most vapor calculations, it is infeasible to use formulas. Instead, it is necessary to use values which have been determined by experiment and listed in tables. The use of these tables will be described later; the Steam Table 394 is an example.

NOTE.—HIGHLY SUPERHEATED VAPORS ARE GASES, if the superheat is sufficiently great, and they do then approximately follow the perfect gas laws.

352. Vapors Are Essential To The Operation Of Most Refrigerating Plants, Many Power Plants And For Many Industrial Processes.—Hence, a knowledge of their properties and behavior is very important to the engineer. Water vapor—steam—is used to generate more power than any other substance; see following Sec. 391. The vapors, ammonia, sulphur dioxide, and carbon dioxide are practically the only substances used as refrigerants in the manufacture of artificial ice; see Div. 18. The examples just stated indicate how extensively vapors are used in industry. All behave similarly even though they have different boiling points. Thus, the general principles stated in this division are true for all vapors. But the properties of only the four important vapors, named above, will be treated in detail.

353. Vapors May Occur In Any One Of Three Conditions: (1) *Saturated vapor* which may be either wet or dry. (2) *Superheated vapor.* (3) *Supersaturated vapor.* Each of these conditions will be discussed separately.

354. Saturated Vapor Fig. 333 (see also discussion and definition given in Sec. 305), is vapor at the temperature corresponding to the boiling point of the liquid at the imposed pressure. As explained in Sec. 315, there is, for each different liquid substance, a certain definite boiling point for each pressure. A

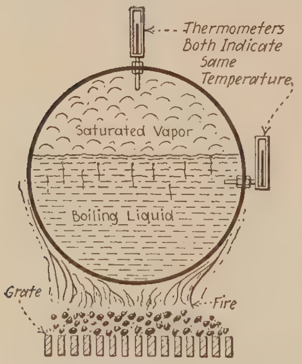


FIG. 333.—Illustrating the meaning of the term "saturated vapor."

substance which is in the vaporous form in a confined space and which is in contact with some of the same substance which is in the liquid state, is always at the same temperature as the liquid and is saturated vapor. When heat is added to a confined (at constant pressure) body of saturated vapor and to the liquid with which it is in contact, more of the liquid vaporizes but the temperature of the liquid and vapor remains constant. Similarly if heat is extracted, more of the vapor will condense but the temperature will also remain constant. The temperature will not change until the liquid is all vaporized or until the vapor is all condensed; see Sec. 322 on "latent heat of vaporization." If the pressure to which the saturated vapor and its liquid are subjected is varied, the temperature of both liquid and vapor will always vary correspondingly with it—but the temperature of the confined vapor will in every case be the same as that of the liquid.

Note.—For A Given Pressure, The Temperature And Density Of A Saturated Vapor Are Fixed.—The temperature and density cannot be changed without also changing the pressure; see Sec. 305; also see Steam Table 394.

355. Saturated Vapors May Be Either Dry Or Wet.—*A dry saturated vapor* is one that does not contain any liquid. It contains just sufficient heat energy to maintain all of the substance in the vaporous form; see also Sec. 305. *A wet vapor* is one that is saturated but it also contains liquid particles, (Fig. 334), either in the form of mist or as fine droplets in suspension. It does not contain sufficient heat energy to maintain all of the substance in the vaporous state.

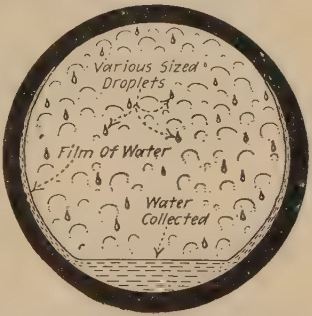


Fig. 334.—Cross-section of steam pipe showing the distribution of water in a main carrying wet steam.

Note.—If Some Of The Heat Of Dry Saturated Vapor Is Absorbed by an outside body, some of the vapor will condense and wet vapor will result.

Note.—In Practice Where The Vapor Is Produced By Boiling, It Is Difficult To Obtain An Absolutely Dry Saturated Vapor, because, if boiling takes place at even a moderate rate, some liquid particles are always carried upward with the rising vapor. Furthermore, when the vapor is transmitted any considerable distance through pipes, it usually loses some heat which causes more vapor to condense (Sec. 301) and consequently produces more liquid in the vapor.

356. Superheated Vapor is vapor the temperature of which is greater than that of the boiling point corresponding to the pressure imposed on it. The temperature of a vapor may be increased above that corresponding to the imposed pressure by adding heat to the vapor (Fig. 335) after the liquid has all been vaporized or after the vapor has been separated from contact with the liquid. Superheated vapor contains more heat energy than that required merely to maintain the substance in the vaporous condition. It contains the additional heat energy required to raise the temperature of the vapor above the temperature corresponding to the pressure. The superheated condition of a vapor in one which is not in thermal equilibrium with the liquid, for if superheated vapor is brought

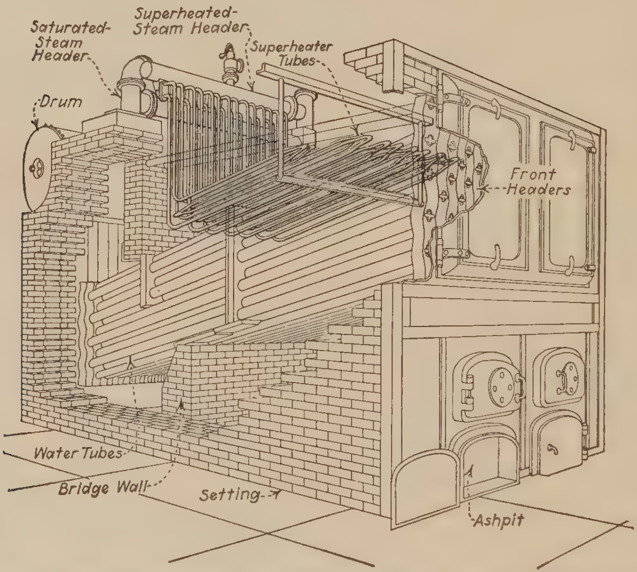


Fig. 335.—"Elesco" superheater applied to a water-tube boiler of the cross-drum type. (*The Superheater Company.*)

in contact with the liquid substance, it will give up that portion of its additional heat which is required to vaporize the liquid, providing it contains that much additional heat. If it does not contain sufficient additional heat to vaporize all the liquid, it will give up all its additional heat and some of the liquid will not be vaporized.

Note.—While Saturated Vapor Can Have Only One Temperature And Density For A Given Pressure, Superheated Vapor Can Have Any Temperature Above The Boiling Point And Any Density less than that of saturated vapor, for the given pressure. At constant pressure the temperature of superheated vapor increases with the heat added.

Note.—The Amount Of Superheat In A Vapor Is Given in terms of the difference between its temperature and that of saturated vapor at the same pressure. Thus, vapor which has a temperature 50° higher than saturated vapor at the same pressure is said to contain "50° of superheat."

357. Supersaturated Vapor is vapor the temperature of which is less and the density of which is greater than that corresponding to the pressure imposed on it. This condition is obtained when vapor is cooled by its own expansion until it contains less heat energy than would the saturated vapor under the same conditions. This condition cannot always be obtained because—after the heat energy of the vapor is reduced to that of saturated vapor under the same conditions, and then more heat is abstracted—some of the vapor usually condenses and the heat in the remaining vapor is the same. Under certain special conditions, however, for some reason not fully understood, condensation does not take place and the vapor changes to the supersaturated condition. This condition is a very unstable one and the vapor soon resumes the saturated condition.

Note.—This Supersaturated Condition Of Vapor Is Ordinarily Of No Importance In Power Plant Practice except to the turbine designer—it occurs only in the expansion in a turbine or other nozzle. It is mentioned here only to show that this condition may exist. It will not be further discussed.

358. Vapors, When Used In Engineering Processes, Do Not Remain In The Same Condition Throughout The Process; That Is, Their "Properties" Change.—At certain points in a process the substance may be all vapor, at other points it may be all liquid, while at intermediate points it may be part liquid and part vapor. The pressure on the vapor may vary through a wide range and also the temperature. With these pressure and temperature changes, the volume of 1 lb. of the substance must also change. The fact that the working substance is used as a vehicle for conveying heat, necessitates its possessing a different quantity of heat at different points or conditions. These several qualities, *pressure*, *temperature*, *specific volume*, *heat content*, and others which are related to one another are spoken of as the *properties of the vapor*.

359. The Various Properties Of Each Vapor Are Interrelated. That is, they depend upon one another; hence, if some of them are given or observed, the others may be found. It was shown in preceding Sec. 354, that for saturated vapor at a given pressure, the temperature is always the same. Thus, if the pressure of saturated vapor is observed, its temperature can be found from a vapor table in which the results of previous experiments are tabulated. Likewise, all the other properties of a given weight of a certain vapor which will be described later, such as latent heat of vaporization, can be found when any two properties, such as the pressure and quality for saturated vapor or the pressure and temperature for superheated vapor, are known. However, if it is known that the vapor is dry and saturated only one other property such as the pressure need be known, since the knowledge that it is dry constitutes the second known property which is "quality."

NOTE.—FOR DRY SATURATED VAPOR, THE PRESSURE NEED NOT BE THE OBSERVED PROPERTY.—Any property may be the observed one and all the other properties may be found from it. In steam practice the pressure is usually observed while in refrigeration practice the temperature is observed. Likewise with wet saturated or superheated vapor any two properties may be observed to determine the remainder. But for wet saturated vapor, temperature and pressure cannot be counted as two properties for one determines the other; hence, another property besides either one of them must be given.

NOTE.—PRESSURE GAGES, THERMOMETERS, AND VAPOR CALORIMETERS are used to determine the properties of the substances at various points. Vapor calorimeters (Sec. 392) determine the percentage of liquid carried with the vapor.

360. By The "Quality" Of Saturated Vapor is meant the percentage of dry vapor present in the given amount of the wet saturated vapor. It is, in this book, usually expressed as a decimal but it is often expressed as a percentage. That is, if 100 lb. of wet vapor contains 2 lb. of liquid and 98 lb. of dry vapor, the quality of the vapor is 98 per cent. or 0.98. It is important to know the quality of a vapor in ascertaining its heat content per pound (see Sec. 365). "Quality" is also used in calculating engine economies. Quality is determined by means of vapor or steam calorimeters, as is explained in Sec. 392.

Example.—Assume that an engine requires 10,000 lb. of dry steam per hour for a given output. It is found that the quality of the steam furnished to it is 94 per cent. Neglecting the heat of liquid in the water, what weight of wet steam must be furnished? Solution.—The 10,000 lb. of steam is 94 per cent. of the weight of wet steam necessary. Then: *the weight of wet steam required* = 10,000 ÷ 0.94 = 10,630 *lb. per hr.*

361. The Properties Of The Vapors Used In Practice Are Arranged In "Vapor Tables."—The values found therein (Tables 394, 395, 399, 400 and 401) have been determined accurately by experiment. They form the basis for many vapor calculations. Such tables must be employed because the properties of vapors cannot be determined from the general gas law (Sec. 248) or other simple formulas. *The values given in the tables are for dry saturated vapors* but they may be used also for wet-vapor computations. When they are so used, the amount of liquid present in the wet vapor must be given consideration. This is necessary because the tables give values which apply only to the vapor and not to the liquid and vapor together; see Sec. 366. The tables given in this division are abstracts of more extensive tables; but they are complete enough for most engineering work except engine, turbine, or refrigeration-compressor designing.

Note.—The Heat-content Values Shown In The Vapor Tables Indicate Only The Heats Of 1 Lb. The Vapor Above 32° F. Liquid, although the liquid at 32° F. does contain some heat. As explained in Sec. 108, some starting point must be chosen because the total heat in a body, that above 0° F. abs., cannot be measured. This arbitrarily chosen point, the liquid state at 32° F., is a convenient one for most vapors. Calculations will not be affected by the temperature which is thus used as this starting point (or datum) above which the total heat of the vapor is considered, for in engineering only the *difference* in heat content between two conditions of the vapor is desired and *not the total heats*. Almost any reasonable temperature other than 32° F. might have been chosen as the standard starting point; but 32° F. *was* chosen. It is convenient and hence is widely used.

NOTE.—THERE ARE TWO TABLES FOR EACH VAPOR.—One table contains the properties of the dry saturated vapor and the other the properties of the superheated vapor. The table of the properties of superheated steam is the only table of superheated vapors given in this volume. The properties of wet vapor can be determined from the table of dry saturated-vapor properties by the method shown in Sec. 366. The properties of supersaturated vapors are not tabulated since this condition of vapor, as stated in Sec. 357, seldom occurs in engineering practice.

362. To Determine The Properties Of A Vapor At Some Pressure Between Those Given In Tables 394, 395, 399, and 400, *interpolate* as explained below and by the following example. This method is quite accurate. There are, however, charts of the properties of vapors, as shown in Fig. 343, from which these intermediate values can be read directly. If the charts are large and accurately made, the values obtained from them will be more accurate than those found by interpolation of the values given in the table. However, most charts are small and not precisely printed, which tends to render them inaccurate. Hence charts should not be used for exact computations unless they have been previously checked with a table of known accuracy. Charts will be further discussed in Sec. 382.

EXAMPLE.—Find the temperature and latent heat of 1 lb. of steam at 154 lb. per sq. in. abs. SOLUTION.—The pressure, 154 lb. per sq. in. abs., is 0.4 of the range from 150 to 160 in Column 2, Table 394. That is, $160 - 150 = 10$ and $154 - 150 = 4$, and $4 \div 10 = 0.4$. Therefore, the temperature at this pressure is approximately 0.4 of the range from 358.5 to 363.6° F., greater than 358.5° F. Thus it will be: $358.5 + 0.4(363.6 - 358.5) = 360.5°$ F. Similarly, the latent heat of steam at 154 lb. per sq. in. abs. is: $863.2 - 0.4(863.2 - 858.8) = 861.5$ *B.t.u.*

363. The Heat Of The Liquid, h (Tables 394, 399, 400 and 401), as given in tables of vapor properties, is the heat in British thermal units required to raise the temperature of 1 lb. of the liquid from 32° F. to that temperature at which the liquid begins to boil at the given pressure, P. In changing a liquid to a vapor under constant pressure, the temperature of the liquid must first be brought up to its boiling point at the given pressure before the liquid can evaporate (Sec. 315). The heat required to do this is called the heat of the liquid.

Note.—The Heat Of The Liquid May Be Found Approximately By Multiplying The Specific Heat Of The Liquid By The Temperature Rise; see Sec. 92. For water the specific heat is approximately 1. Hence the heat of the liquid for water vapor or steam then must be approximately equal to the difference in temperature between the temperature under consideration and 32° F. See Table 394, column 5.

Example.—The heat of 1 lb. of liquid (water) at 261° F., as shown by Steam Table 394, is 229.6 B.t.u. *The temperature difference between* 261 *and* 32° *F.* $= 261 - 32 = 229°$ *F.* This value is nearly equal to the actual heat of liquid in B.t.u.—229.6—as shown by the steam table. The correct value is the one given in the steam table.

Note.—The Heat Of The Liquid Increases With The Pressure.—Since the temperature increases with the pressure, the heat of the liquid must also increase with the pressure.

Note.—Vapors Are Often Used Below 32° F. In Refrigeration Processes (see Tables 399, 400, and 401). For temperatures below 32° F., the heat of the liquid given in the table must be extracted from, instead of added to the liquid at 32° F. to bring it to the temperature under consideration. Hence, the heat of the liquid is given the negative sign in the vapor tables when the temperature of the liquid is below 32° F. At 32° F. the heat of the liquid must be zero.

364. The Latent Heat Of Vaporization, L, (see Sec. 322 for definition) is also given in the vapor tables. The value of the latent heat of vaporization decreases as the imposed pressure increases (see Tables 394, 399, 400, and 491 for saturated vapors) until the critical pressure is reached; there it becomes zero. The latent heat of vaporization is, as explained in Sec. 325, divided into two parts: (1) *The external latent heat of vaporization*—external-work heat—which is equivalent to the amount of mechanical work done by the vapor in expanding from the liquid to the vapor state. (2) *The internal latent heat of vaporization*—disgregation heat—which is the increase in internal heat energy accompanying the vaporization; see also Sec. 107. The values for these two parts of the latent heat of vaporization are also given in the saturated-vapor tables in the columns headed L_E and L_I respectively. It is a useful fact to remember that it requires about 1,000 B.t.u. (see Steam Table 394) to vaporize 1 lb. of water at atmospheric pressure.

NOTE.—NO VALUE FOR THE LATENT HEAT OF VAPORIZATION IS GIVEN IN TABLE 395 OF THE PROPERTIES OF SUPERHEATED WATER VAPOR. —These values can be found from the table of the properties of saturated vapors under the latent heats of vaporization for the same pressure; see following example. The latent heat depends on the pressure and not on the amount of superheat.

NOTE.—THE TERMS "LATENT HEAT OF THE VAPOR" and "HEAT OF VAPORIZATION" are sometimes used instead of "Latent Heat of Vaporization."

EXAMPLE.—Find the amount of heat that was required to vaporize 10 lb. of steam which is at 160 lb. per sq. in. gage and has a temperature of 500° F. SOLUTION.—From saturated-steam Table 394, the temperature of steam which is at 160 lb. per sq. in. gage pressure, is found to be only 370.8° F. Hence the steam given in this example must be superheated steam. But this does not affect the solution of the problem because the heat of vaporization of superheated steam is the same as that for saturated steam at same pressure. In saturated-steam Table 394 on the horizontal line with 160 lb. per sq. in. gage pressure in the **L** (heat-of-vaporization) column is the value "852.7." This is the heat in B.t.u. required to vaporize 1 lb. of steam. To vaporize 10 lb. of steam: $10 \times 852.7 = 8{,}527$ *B.t.u.* are required.

365. The Total Heat Of A Vapor, ($\mathbf{H}_D$ Column 4, Table 394), is the amount of heat which must be supplied to 1 lb. of the liquid which is at 32° F, to convert it, at constant pressure, into vapor at the temperature and pressure considered. This value is given in both the tables of the properties of saturated vapors and those of the properties of superheated vapors. The total heat is, for dry saturated vapor, the sum of the heat of the liquid, **h**, and the latent heat of vaporization, **L**; see Sec. 108. The total heat of any dry saturated vapor increases with the pressure. For superheated vapors, the total heat (Table 395) includes not only the heat of the liquid and the latent heat of vaporization but also the additional heat required to superheat the vapor.

NOTE.—THE TOTAL HEAT OF A VAPOR DEPENDS ON HOW THE VAPOR IS HEATED.—The total heat given in the tables is for heating at constant pressure. If the liquid is heated in some other manner, as at constant volume, the total heat added would be different.

EXAMPLE.—Find the amount of heat which must be supplied to 53 lb. of water at 59° F. to convert it into saturated steam at 250.3° F. Do not use the $\mathbf{H}_D$ values in Column 4 of Table 394.

SOLUTION.—The heat of liquid at 250.3° F. is 218.8 B.t.u. per lb. At 59° F. it is 27.08 B.t.u. per lb. The amount of heat that must be added to the liquid to raise it to the required temperature is then: 218.8 − 27.08 = 191.72 *B.t.u. per lb.* The heat required to vaporize the liquid at 250.3° F. is 945.1 B.t.u. per lb. Hence, the total heat required is: (945.1 + 191.72) × 53 = 1,136.82 × 53 = 60,250 *B.t.u.* for 53 lb. Note.—This result would be obtained in practice by subtracting the heat of liquid, 27.08 B.t.u., from the total heat of steam 1,163.9 giving 1,136.82 B.t.u. per lb. as before.

366. The Total Heat Of A Wet Saturated Vapor Cannot Be Obtained Directly From The Vapor Tables.—However, it can be calculated when the quality is known by the use of the following formula, the derivation of which is given below:

$$\mathbf{H_W = h + xL} \qquad \text{(B.t.u. per pound)} \tag{242}$$

Wherein: $\mathbf{H_W}$ = the total heat of wet vapor, in British thermal units per pound. **h** = the heat of liquid at the temperature of the wet vapor, in British thermal units per pound. **x** = the quality of the wet vapor, expressed decimally; that is, the fraction of the mixture that is vaporized. **L** = the latent heat of dry saturated vapor at the pressure of the wet vapor.

Example.—Find the total heat of 1,100 lb. of wet ammonia vapor having a quality of 96 per cent. The temperature of the vapor is 60° F.

Solution.—From Table 400 for the vapor at 60° F., **h** = 30.9 *B.t.u. per lb.* and **L** = 522 *B.t.u. per lb.* By For. (242): the total heat per lb., $\mathbf{H_W = h + xL} = 30.9 + (0.96 \times 522) = 30.9 + 501.1 = 532$ *B.t.u. per lb.* For 1,100 lb.: *the total heat* = 1,100 × 532 = 585,200 *B.t.u.*

Derivation.—Wet vapor (Sec. 355) has liquid particles suspended in it. Since the liquid particles contained in the wet vapor are at the same temperature as the vapor, the heat of the liquid, **h**, contained in a given weight of wet vapor must be the same as that contained in the same weight of dry saturated vapor at the same pressure. But also, the vapor portion of wet vapor contains latent heat of vaporization. Now, by definition, the weight of dry vapor in 1 lb. of wet vapor is equal to the quality, **x**, of the vapor expressed decimally. Hence, the latent heat in 1 lb. of wet vapor must equal the latent heat, **L**, of dry saturated vapor times the quality. That is, *the latent heat present in* 1 *lb. of wet vapor* = **xL.** Hence the total heat present is:

$$\mathbf{H_W = h + xL} \qquad \text{(B.t.u. per lb.)} \tag{243}$$

which is the same as For. (242).

367. The Total Heat Of Superheated Vapor Can Be Computed When No Table Of Superheated-vapor Properties Is At Hand.—The temperature and pressure of the vapor must both be known. For steam, find the temperature in Steam

Table 394 corresponding to the pressure of the vapor. The difference between this temperature and the observed temperature is (Sec. 356) called the *degrees of superheat.* Then find, from the graph of Fig. 336, the mean specific heat of superheated steam for this pressure and degree of superheat. Now, the total heat of superheated vapor is:

(244) $$\mathbf{H}_S = \mathbf{H}_D + \mathbf{C}T_S$$ (B.t.u. per lb.)

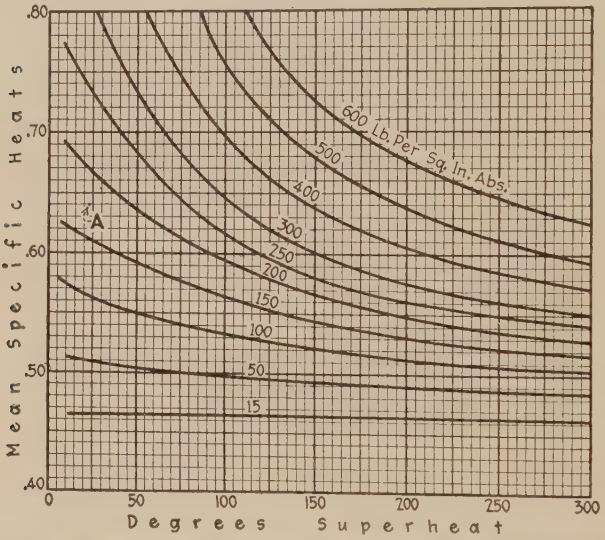


Fig. 336.—Chart showing mean specific heat of superheated steam for various pressures and degrees of superheat.

Wherein: $\mathbf{H}_S$ = the total heat of superheated vapor, in British thermal units per pound. $\mathbf{H}_D$ = the total heat of saturated vapor at the same pressure as that of the superheated vapor, in British thermal units per pound. $\mathbf{C}$ = the mean specific heat of superheated vapor at the pressure and degrees of superheat considered; for steam see Fig. 336; for other vapors see note below; T_S = the degrees of superheat of the vapor, in degrees Fahrenheit.

Example.—A certain volume of steam has a temperature of 397° F. and a pressure of 180 lb. per sq. in. abs., what is the total heat per pound? Solution.—The temperature corresponding in Steam Table 394, to

180 lb. per sq. in. abs. is 373.1° F. There are, therefore: 397 − 373.1 = 23.9° F. *of superheat.* The mean specific heat of superheated steam under these conditions is (*A*, Fig. 336) 0.64. Hence, by For. (244), the total heat of superheated steam: $\mathbf{H}_S = \mathbf{H}_D + \mathbf{C}T_S = 1{,}196.4 + (0.64 \times 23.9) = 1{,}211.3$ *B.t.u. per lb.*

Note.—The Mean Specific Heats Of Superheated Ammonia, Carbon Dioxide, And Sulphur Dioxide, throughout the ordinary working ranges, may be taken as: ammonia, 0.52; carbon dioxide, 0.21; sulphur dioxide, 0.15. These are specific heats at constant pressure, Sec. 267.

368. The Specific Volumes Of Vapors (the volumes of 1 lb.) are given in the vapor tables for dry saturated vapors and for superheated steam. The specific volumes of superheated ammonia, carbon dioxide, and sulphur dioxide may be found with reasonable accuracy by applying the general gas law and the constants given in Div. 8. The specific volumes of wet vapors may be computed, with reasonable accuracy, by For. (245) below. If extreme accuracy is desired For. (246) may be used.

$$V_W = \mathbf{x}V_D \qquad \text{(cu. ft. per lb.)} \tag{245}$$

Wherein: V_W = the specific volume of the wet vapor, in cubic feet per pound. $\mathbf{x}$ = the quality of the vapor, expressed decimally. V_D = the specific volume of dry saturated vapor of the same pressure, in cubic feet per pound; V_D can be found from the vapor tables.

Derivation.—Since 1 lb. of the wet vapor contains $\mathbf{x}$ lb. of dry saturated vapor and $(1 - \mathbf{x})$ lb. of liquid at the boiling temperature, the specific volume of the wet vapor must be the sum of the volumes occupied by $\mathbf{x}$ lb. of dry saturated vapor and $(1 - \mathbf{x})$ lb. of liquid. If V_L is the specific volume of the liquid at the boiling temperature, then the volume of $(1 - \mathbf{x})$ lb. of liquid will be $(1 - \mathbf{x}) \times V_L$ cu. ft. Also, the volume of $\mathbf{x}$ lb. of dry saturated vapor will be $\mathbf{x} \times V_D$ cu. ft. Hence, the specific volume of the wet vapor,

$$V_W = (1 - \mathbf{x})V_L + \mathbf{x}V_D \qquad \textit{(cu. ft.)} \tag{246}$$

But, the specific volume of the liquid is ordinarily very small as compared with that of the dry saturated vapor. Hence, except for very wet vapor ($\mathbf{x}$ very small), only a negligible error is introduced by disregarding the term of For. (246) which expresses the volume of the liquid. When this term is disregarded, For. (245) results.

Example.—What is the specific volume of steam of 80 per cent. quality at 125 lb. per sq. in. abs.? Solution.—From steam Table 394, at 125 lb. per sq. in. abs., $V_D = 3.583$ cu. ft. per lb. Hence, by For. (245), the *specific volume of the wet steam* $= V_W = xV_D = 0.80 \times 3.583 = 2.866$ *cu. ft. per lb.*

NOTE.—TO FIND THE QUALITY OF WET STEAM WHEN ITS SPECIFIC VOLUME AND ITS PRESSURE OR TEMPERATURE ARE KNOWN, the following formula—a transposed form of For. (245)—may be used

$$x = \frac{V_W}{V_D} \qquad \text{(decimal)} \tag{247}$$

EXAMPLE.—If 2 lb. of steam at 281° F. are contained in an engine cylinder whose volume is 12 cu. ft., what is the quality of the steam? SOLUTION.—The *specific volume* $= V_W = 12 \div 2 = 6$ *cu. ft. per lb.* At 281° F., by Table 394, the specific volume of dry saturated steam is 8.51 cu. ft. per lb. Hence, the steam in the cylinder is *wet.* Then, by For. (247), the *quality* $= x = V_W/V_D = 6 \div 8.51 = 0.705$ or 70.5 *per cent.*

369. The "Internal Heat" or "Internal Energy" Of A Vapor (see Sec. 107, for definition) can readily be computed. As explained in Sec. 103, nearly all of the heat of the liquid (**h** in the vapor tables) represents vibration heat and is therefore internal heat. Likewise, during vaporization, a great portion of the latent heat of vaporization is stored as internal energy (in Table 394 the latent heat is divided into internal and external heats). For any liquid, vapor, or mixture of liquid and vapor, the internal energy per pound (measured above that of the liquid at 32° F.) may be found from the tables by the formula:

$$\mathbf{I} = \mathbf{H} - 0.185{,}2PV \qquad \text{(B.t.u. per lb.)} \tag{248}$$

Wherein: **I** = the internal energy of the liquid or vapor, in British thermal units per pound. **H** = the heat content (Sec. 365) of the liquid or vapor, in British thermal units per pound. P = the pressure of the vapor, or the pressure at which the liquid will boil at its temperature, in pounds per square inch absolute. V = the specific volume of the liquid or vapor, in cubic feet per pound.

DERIVATION.—Formula (248) is the direct result of transposition and simplification of the formula which is used by the compilers of the vapor tables as the definition of heat content, namely:

$$\mathbf{H} = \mathbf{I} + \frac{144PV}{778} \tag{249}$$

EXAMPLE.—What is the internal energy of 1 lb. of dry saturated water vapor at 366° F.? SOLUTION.—By Table 394, for the given condition: $\mathbf{H} = 1{,}195.0$ B.t.u. per lb.; $P = 165$ lb. per sq. in. abs.; $V = 2.753$ cu. ft. per lb. Hence, by For. (248), the *internal energy* $= \mathbf{I} = \mathbf{H} - 0.185{,}2PV = 1{,}195.0 - (0.185{,}2 \times 165 \times 2.753) = 1{,}110.8$ *B.t.u. per lb.*

EXAMPLE.—What is the internal energy of 1 lb. of steam at 200 lb. per sq. in. abs. and superheated by 150° F.? SOLUTION.—By Table 395, for the given conditions, $\mathbf{H} = 1{,}282.6$ B.t.u. per lb., and $V = 2.86$ cu. ft. per lb. Hence, by For. (248), the *internal energy* $= \mathbf{I} = \mathbf{H} - 0.185{,}2\ PV = 1{,}282.6 - (0.185{,}2 \times 200 \times 2.86) = 1{,}176.6$ *B.t.u. per lb.*

EXAMPLE.—What is the internal energy of 1 lb. of steam whose quality is 0.75 and whose temperature is 312° F.? SOLUTION.—By Table 394, at 312° F.: $\mathbf{h} = 282$ B.t.u. per lb. $\mathbf{L} = 900.3$ B.t.u. per lb. $V_D = 5.47$ cu. ft. per lb. $P = 80$ lb. per sq. in. abs. Hence, by For. (242): the *total heat* $= \mathbf{H}_W = \mathbf{h} + \mathbf{x}\mathbf{L} = 282 + (0.75 \times 900.3) = 957.2$ *B.t.u. per lb.* Now by For. (245), the *specific volume* $= V_W = \mathbf{x}V_D = 0.75 \times 5.47 = 4.10$ *cu. ft. per lb.* Hence, by For. (248), the *internal energy* $= \mathbf{I} = \mathbf{H} - 0.185{,}2\ PV = 957.2 - (0.185{,}2 \times 80 \times 4.10) = 896.4$ *B.t.u. per lb.*

370. Heat Energy Transfer May Be Expressed As The Product Of "Entropy" And "Absolute Temperature."—

Every kind of energy or work may, as is explained below, be expressed as the product of two factors. Now, early in the study of heat phenomena it became evident to the investigator Clausius that it would be desirable to similarly express heat energy as the product of *two* factors. One of the factors he decided should be *absolute temperature.* The other factor, which he proposed—and which when multiplied by average absolute temperature would give heat energy—he named *entropy.* It might quite as well have been christened with any other distinctive name. Entropy will now be explained.

EXAMPLE.—*Illustrating How All Energy Change Is The Product Of Two Factors.* In representing energy by the area of a graph, one of these factors is represented by vertical distances and the other by horizontal distances. Thus, for example (Fig. 337):

(250) *Mechanical Energy Change = (Distance Change) × (Average Force)*

That is (Fig. 337), if it requires a force of 20 lb. to pull a weight, W, along a horizontal surface and the weight is pulled a distance of 40 ft. then: *the energy expenditure* $= 20 \times 40 = 800$ *ft.-lb.;* this 800 ft.-lb. of energy is represented by the area of $ABCD$ shown in Fig. 337-*II*. Also:

(251) *Mechanical Energy Change = (Volume Change) × (Average Pressure)*

That is, if the expanding steam in the engine cylinder, *C*, of Fig. 338 moves the engine piston, *P*, through a volume of 1.8 cu. ft. and the mean effective pressure from *B* to *E* (as determined with a steam-engine indicator) is 10,282 lb. per sq. ft., then the mechanical energy expended by the steam (Sec. 99) will be: *External work* = *pressure* × *change in volume* = 10,282 × 1.8 = 18,507 *ft.-lb.* (The work done, if any, in pushing the exhaust steam out of right end of the cylinder, *L*, is here disregarded.) This energy expenditure—18,507 ft.-lb.—is represented by the shaded area *ABED* within the diagram of Fig. 338-*II*. This is similar to any steam-engine indicator diagram for ½ a revolution. Also, in similar manner, it can be demonstrated that:

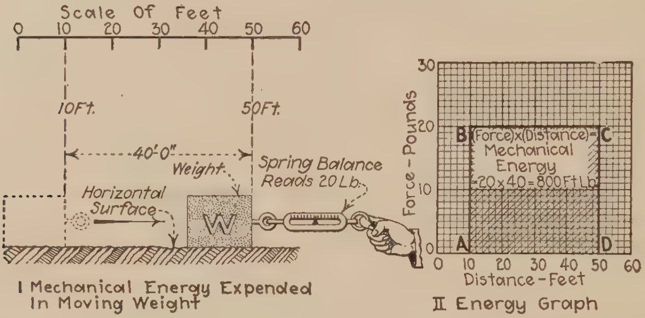


Fig. 337.—Showing how the product of two factors "force" and "distance" equals "mechanical energy" and how they may be employed in representing mechanical energy as an area.

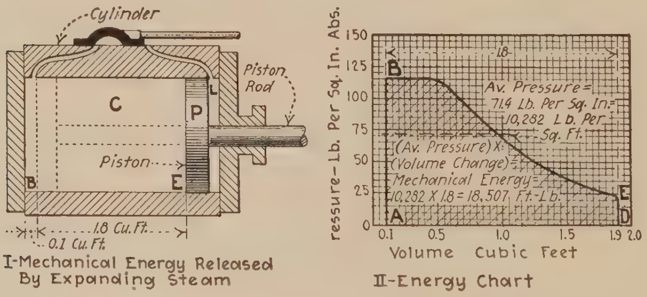

Cylinder
Piston Rod
C
L
P
Piston
B
E
1.8 Cu. Ft.
0.1 Cu. Ft.
I-Mechanical Energy Released By Expanding Steam
ressure–Lb. Per Sq. In. Abs.
150
125
100
75
50
25
0
1.8
B
Av. Pressure = 71.4 Lb. Per Sq. In. = 10,282 Lb. Per Sq. Ft.
(Av. Pressure) X (Volume Change) = Mechanical Energy = 10,282 X 1.8 = 18,507 Ft.-Lb.
A
E
D
0.1 0.5 1.0 1.5 1.9 2.0
Volume Cubic Feet
II-Energy Chart

Fig. 338.—Showing how the product of two factors "pressure" and "volume" equals "mechanical energy" and how they may be employed in representing mechanical energy as an area.

(252) *Hydraulic Energy Change* = (*Weight of Water Change*) × (*Average Height*)

And also:

(253) *Electrical Energy Change = (Quantity of Electricity Change) × Average Voltage)*

And, it can also be shown that for both of these forms of energy—Fors. (252) and (253) above—that the product of the two factors may be represented by an area. Now *heat is also a form of energy and, likewise, any change in it is the product of two factors and may be represented by an area.* As above stated, one of these factors is *average absolute temperature;* the other is called *entropy.*

Thus:

(254) *Heat energy change = (Entropy change) × (Average Abs. Temp.)*

The following example (Fig. 339) illustrates the application of the above equation. Example.—In Fig. 339-*I* the 1 lb. of water, *L*, is at 212° F. (672° F. abs.). Now, heat is added until all of this water is vaporized into 1 lb. of steam *V*, at 212° F. (672° F. abs.) and atmospheric pressure. Compute, using entropy and absolute-temperature values, the heat energy which has been added as heat to the water, *L*, to thus vaporize it into steam, *V*, and also represent as an area on a graph this added heat energy. Solution.—Now from Steam Table 394, horizontally opposite "212° F.," it is found that the entropy of 1 lb. of the liquid—water—is 0.311,8; also it is found that the entropy of 1 lb. of the vapor, *V* (steam) at 212° F. is 1.756,5. The temperature does not change while a liquid is being vaporized (Sec. 322); hence: *The average absolute temperature* = 212 + 460 = 672° F. *abs.* Therefore, to produce this

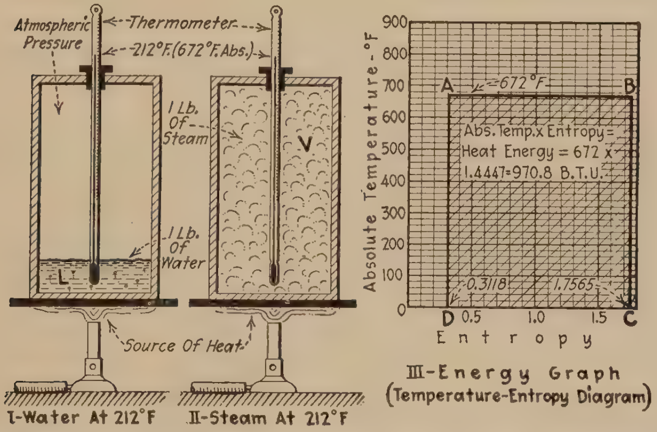


Fig. 339.—Showing how the product of two factors "absolute temperature" and "entropy" equals "heat energy" and how they may be employed in representing heat energy as an area.

vaporization: *The heat energy transfer* = (*Entropy change*) × (*Av. abs. temp.*) = (1.756,5 − 0.311,8) × 672 = 1.444,7 × 672 = 970.8 *B.t.u.* This heat energy transfer is shown graphically in Fig. 339-*II* in which the shaded area *ABCD* is equivalent to the heat energy which was transferred.

The discrepancy between this value "970.8" and that given in Steam Table 394 of "970.4" is due to the usual assumption which was made in this example, that absolute zero is at −460° F.; actually it is at −459.6° F. instead of as given in the example.

This (Fig. 339) illustrates the simplest form of temperature-entropy problem—but the general principle which it discloses holds for all temperature-entropy problems. The example of Fig. 339 is simple because the temperature *AB* remains constant during the heat transfer. Except during changes of state (Fig. 339 for example) and during isothermal expansions, the temperature does change while heat energy is being transferred, as heat. When the temperature changes during heat transfer, the line on the corresponding temperature-entropy graph, which corresponds to the line *AB* Fig. 339, is not generally straight but becomes a curve. This is further explained hereinafter.

371. A Good General Definition of Entropy Change is *heat-energy transfer to or from a substance, per degree of average absolute temperature.* By "heat-energy transfer" is here meant energy which is transferred, *as heat*, from the substance to some external object, energy which is transferred, *as heat*, from some external source to the substance, or heat which is transferred within the substance itself due to *friction* of the substance. As is explained in the following note, entropy does not recognize heat energy which is due to external work. Also, the "average absolute temperature," as will be shown, must be determined in accordance with certain rules; it is the average of all of the absolute temperatures to which the substance has been subjected. It is *not* merely the mean of the initial and the final temperatures.

NOTE.—ENTROPY IS A PROPERTY OF SUBSTANCES AND DOES NOT CHANGE WHEN INTERNAL ENERGY IS TRANSFORMED INTO EXTERNAL WORK.—If the substance at some definite condition is assumed as a starting point, it can be proved that, in passing to a second condition during a condition change, the entropy change will have a certain value, regardless of how the change was effected. This would not be true of the work done or heat added during the change. Since entropy change is dependent only on the initial and final conditions of the substance, it follows that entropy is a property of the substance.

Now, when internal energy is transformed into external mechanical work during a frictionless adiabatic (or isentropic, Sec. 385) condition change (no heat being interchanged between the substance and external objects, and no heat being generated by friction of the substance), there is no entropy change because there is no heat transfer. But, since internal energy is transformed into external work, the total heat (Sec. 108) of the substance must be reduced. Hence, entropy does not recognize heat energy which is due to external work.

372. Entropy Is Imperceptible To The Senses; its effects cannot be measured with instruments. Entropy values can be determined only by computation. The values of all other thermal properties of substances, such for example as temperature and pressure, *can* be measured with instruments. For these reasons, the significance of entropy may be difficult to understand. But if an entropy value is thought of merely as a previously determined multiplier, factor, or coefficient, which varies with the thermal condition of a substance, then the entropy idea should give no trouble. It is really not necessary—but it is desirable—to understand what entropy is, in order to use entropy values. In practice, values for entropy changes are usually taken from vapor-property tables (which practically always give entropy values for 1 lb. of the substance); for examples see Tables 394 and 395.

NOTE.—ANY SUBSTANCE WHICH CONTAINS HEAT WILL HAVE ENTROPY.—However, it is a fact that the entropy idea is employed most frequently in connection with discussions of the thermal performance of gases and vapors—for which reason the treatment of entropy for the present book is included in this division. Another reason for the introduction of this treatment here is that it is desirable to understand "entropy" before using the entropy values which are given in the following tables of vapor properties.

373. The Principal Uses Of Entropy are: (1) *It renders possible the representation as an area on a graph, the heat energy which is transferred, as heat, to or from a substance.* The diagrams (see Fig. 339-*III* and following similar illustrations) which represent heat as an area are called *temperature-entropy* diagrams. These diagrams are useful in picturing the heat-energy transfers and cycles (see Div. 12) which occur in an engine or during any desired vapor or gas process; they provide a graphic presentation of the ideas which are involved and relieve the mind of the necessity of holding, or of endeavoring to follow, a multitude of simultaneous conceptions. Temperature-entropy diagrams are ordinarily of little or no use to the practical operating engineer. (2) *It renders possible the plotting of heat-entropy charts* (Fig. 343) *and temperature-entropy charts.* From these charts the values of the various properties of the vapor, as the values change during frictionless adiabatic (isentropic) expansions, (Sec. 385) may be read directly. These changes in properties could not be plotted in this way on the charts without employing entropy—and they could not be determined except from the charts or by employing entropy without many complicated calculations.

374. The Absolute Entropy Of A Substance at any condition would be the total heat energy transferred to it, as heat, per degree of average absolute temperature to bring it to that condition. This "degree of average absolute temperature" would be the average of all of the absolute temperatures which the substance experienced from the condition of zero heat content up to the temperature of the stated condition. But it is impossible to determine the absolute entropy of a substance —in fact, it is always infinite—because nothing definite is known concerning the total heat contents of substances, or of their specific heats at very low temperatures. However, this does not affect the usefulness of entropy. In practice it is, as will be shown, *changes in entropy* at the temperature of practice that are always of interest, rather than absolute entropy. Only changes of entropy enter into heat transfers.

NOTE.—THE ZERO OF ENTROPY, IN DEALING WITH VAPORS, is arbitrarily taken as the absolute entropy—whatever it may be—of the liquid substance at 32° F. That is, the change that the entropy of a vaporous substance undergoes during any process wherein its condition is changed from the liquid state at 32° F., is said to be its entropy at the end of the process (at its final condition). The liquid state at 32° F., since it has been taken as the starting point or arbitrary zero of heat content (Sec. 108), is also for this reason a very convenient starting point for the measurement of entropy. Understand that this 32° F. is, for entropy, also an arbitrary or selected starting point.

NOTE.—"ABSOLUTE ENTROPY" SHOULD NOT BE CONFUSED WITH "TOTAL ENTROPY."—Total entropy (symbol n_D or n_S), as given in the vapor-property tables, is generally understood to mean the sum of the *entropy per pound of the liquid*, $\mathbf{n}_L$; *the entropy per pound of vaporization*, $\mathbf{n}_V$; and *the entropy per pound of superheat*, $\mathbf{n}_S$ if any —all measured from the arbitrary zero as stated above. Two or all three of these entropy values are usually given in tables of vapor properties; see Table 394 for example.

375. The "Change In Entropy" Of A Substance, *between two thermal conditions, is the heat energy transferred to the substance, as heat, per degree of average absolute temperature between the two conditions.* Or, in other words: The change in entropy between two thermal conditions is a value such than when it is multiplied by the proper average of all of the absolute temperatures which the substance experienced during the heat transfer between the two conditions, it will give as a product the total heat energy added to or abstracted from the substance—as heat—during the transfer. See also the notes and explanations below.

376. The General Formulas For Entropy Change during a heat transfer (their derivation follows from the definitions given in Sec. 375) are:

$$\mathbf{Q} = \frac{\mathbf{n}}{\mathbf{T}_A} \qquad \text{(B.t.u. per lb.)} \tag{255}$$

or

$$\mathbf{n} = \frac{\mathbf{Q}}{\mathbf{T}_A} \qquad \text{(B.t.u. per lb. per avg. abs. °F.)} \tag{256}$$

and

$$\mathbf{T}_A = \frac{\mathbf{Q}}{\mathbf{n}} \qquad \text{(average abs. °F.)} \tag{257}$$

Wherein: $\mathbf{Q}$ = heat-energy change, as heat, per pound of the substance during the heat transfer. $\mathbf{T}_A$ = *average* absolute temperature, during the heat transfer; that is; the average of *all* of the absolute temperatures to which the substance has been subjected during the transfer. $\mathbf{n}$ = change in entropy during the heat transfer. Note that $\mathbf{Q}$ may be expressed in any heat-energy unit and that $\mathbf{T}_A$ may be expressed in any absolute-temperature unit, then the entropy change, $\mathbf{n}$, will be in terms of the quotient of these two units. But when $\mathbf{Q}$ is in British thermal units per pound and $\mathbf{T}_A$ is in average absolute degrees Fahrenheit, then $\mathbf{n}$ will be in British thermal units per pound per average absolute Fahrenheit degree, as indicated after each of the above equations.

NOTE.—ENTROPY RECOGNIZES ONLY ENERGY WHICH IS ADDED OR ABSTRACTED AS HEAT—because of the definition of entropy. It does not recognize energy which is added to a substance by mechanical work being done on the substance, in spite of the fact that such energy may ultimately be converted to heat within the substance. Nor does entropy recognize energy which is lost from a substance by virtue of the doing of mechanical work by the substance. Thus, *during the frictionless adiabatic* isentropic, Sec. 385, *expansion or compression* (Sec. 388) *of a vapor or a gas there is no change of entropy* of the vapor or gas. If mechanical work is done in compressing a gas, adiabatically and without friction, the temperature of the gas will be increased thereby but the entropy of the vapor or gas will not be changed during the process, because no heat energy is added as heat. Similarly, when a vapor or gas expands adiabatically and without friction it will do mechanical work but there will be no change in entropy because in the process no energy has been lost as heat. (It is apparent then that *entropy recognizes only vibration heat, Sec.* 97, *and disgregation* heat, Sec. 98; it does not recognize external-work heat.)

377. How The Value Of The Change In Entropy For A Heat Transfer May Be Determined will now be explained in connection with Fig. 340. Entropy-change values seldom, if ever, have to be thus computed in practice because they are given in the vapor tables. The following approximate method is presented only to insure that the reader may have a better conception of the entropy idea. It is not given as a method to be followed in practice.

EXPLANATION.—For simplicity consider 1 lb. of a substance which is assumed to have a specific heat of "1." Assume that it is heated from 32° F. (492° F. abs.) to 352° F. (812° F. abs.). Assume that the state of the substance does not change. It will be shown (Fig. 340) how the entropy of this substance increases as the heat energy is added to it, as heat, in 10 B.t.u. increments. The first 10 B.t.u. of heat which is added will, since the specific heat is "1" raise its temperature by 10° or from 492° F. to 502° F. abs. as indicated at *D*, Fig. 340. Now, by For. (256): $\mathbf{n} = Q/T_A$. The heat energy added, Q, is 10 B.t.u. During this addition, the average absolute temperature may, since the increase in temperature for each increment is small, be taken as ½ (*initial temperature* + *final temperature*), for each increment. Hence: $T_A = (492 + 502) \div 2 =$ 497° *F. abs.* Therefore, $\mathbf{n} = 10 \div 497 = 0.020{,}1$ *B.t.u. per lb. per avg.* ° F. *abs.* Now the distance *AC* is made to scale equal to 0.020,1. The area, 1, (Fig. 340) will then be equivalent to the 10 B.t.u. of heat which was added—because: 0.020,1 × 497 = 10 *B.t.u.*

Similarly, the next heat-energy addition of 10 B.t.u., which will raise the temperature of the substance from 502 to 512° F. abs., will be represented in Fig. 340 by the area 2. Thus: $\mathbf{n} = Q/T_A = 10 \div [(502. + 512.) \div 2] = 10 \div 507 = 0.019{,}7$ *B.t.u. per lb. per avg.* ° F. *abs.* Therefore, area 2 is layed out 0.019,7 entropy units wide.

In like manner, the change in entropy due to each successive 10-B.t.u. heat-energy increment can be found and plotted on the graph.

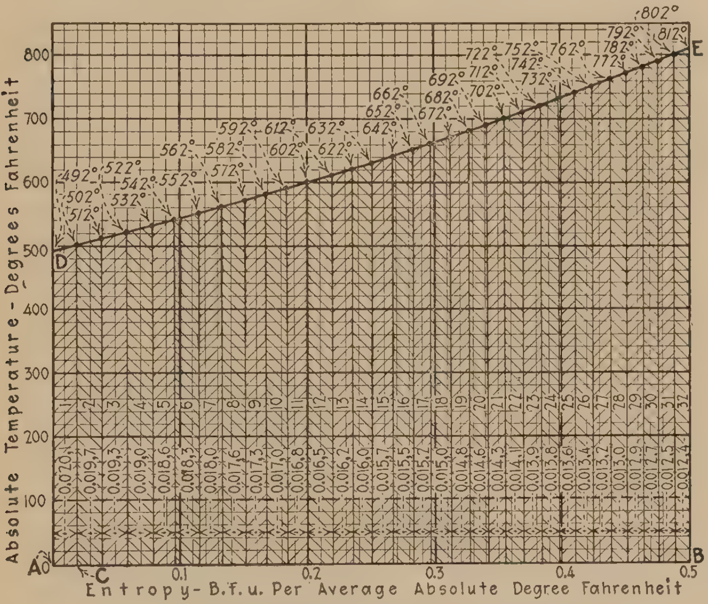


FIG. 340.—Illustrating the method of computing entropy.

Now note that while the *areas* of each of the strips 1, 2, 3 . . . 31, 32 are equal, and that each is equivalent to a heat addition of 10 B.t.u., the *widths* of the strips decrease toward the right. It is obvious that this decrease is necessary because, since the heights (temperatures) of the strips increase as heat is added, the widths of the strips must decrease if their areas are to be all equal. The total entropy change for this total heat addition of 10 × 32 = 320 *B.t.u.* is 0.5 B.t.u. per avg-° F. abs., as shown by the distance *AB*.

It should be understood that the method above described is an approximate one. Its degree of accuracy is determined by the smallness of the heat increments—the smaller the increments the more accurate the result. By applying the calculus the heat increments may be made infinitely small, whereby the entropy change can be determined with absolute accuracy. The small error which results from the application of the method of Fig. 340 is due to the assumption that the short line connecting any two temperature increment points on the curve *DE*, is a straight line—whereas actually it is a curve.

NOTE.—CHANGE IN ENTROPY FOR CHANGE OF STATE is exactly equal to the heat transfer divided by the absolute temperature at which the change of state occurs. This follows since the temperature always remains constant (Sec. 96) during a change of state, under which condition the "average temperature" must equal the constant temperature which obtains during the change. That is, for a change of state:

$$\text{(258)} \qquad n = \frac{Q}{T} \qquad \text{(B.t.u. per lb. per °F. abs.)}$$

378. Temperature-entropy Diagrams Show Heat Energy As An Area.—In the temperature-entropy diagram for steam shown in Fig. 341, all of the heat-energy transfers required

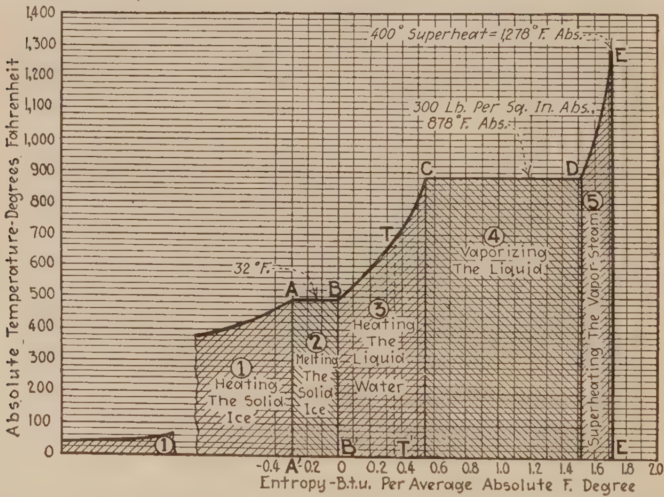


FIG. 341.—Temperature-entropy diagram showing the heat energy which must be added to change 1 lb. of ice into 1 lb. of superheated steam, comprising: (1) Heating the solid. (2) Melting the solid. (3) Heating the liquid. (4) Vaporizing the liquid. (5) Heating the vapor, called "superheating."

to change 1 lb. of ice from near absolute zero (−460° F.) into steam at a constant pressure of 300 lb. per sq. in. abs. and then into superheated steam at 1,278° F. abs. are shown. The plotted values are taken from Steam Tables 394 and 395.

EXPLANATION.—At absolute zero the ice would contain no heat. If heat is transferred to the ice its temperature increases, the relation being shown by the path *OA*. The area, 1, under this path, *OA*, represents the amount of heat-energy transfer required to heat the solid ice to the temperature at *A*. When *A* is reached, which is at 32° F. (492° F. abs.) any further addition of heat does not increase the temperature of the ice but causes it to melt—to change state. This melting continues until all of the ice is melted and the point, *B*, is reached. The area, 2, under *AB*, represents the amount of heat transfer required to melt the ice.

The addition of more heat causes the temperature of the substance—now water—to rise again at such a rate that the area under any portion of *BC*, as *B′BTT′*, represents the heat energy added during the change in temperature from 32° F. to the temperature *T*. The area, 3, under *BC* represents the heat-energy addition which was necessary to raise the temperature of the water from 32° F. to 418° F., or 878° F. abs.—which temperature is that of steam at a pressure of 300 lb. per sq. in. abs. This area 3, therefore, represents the heat of the liquid for steam at the pressure 300 lb. per sq. in. abs. After the temperature *C* is reached, which is the boiling temperature of the water for the 300 lb. per sq. in. pressure exerted upon it, any further addition of heat does not increase the temperature but again changes the state; it vaporizes the water into steam. Point *D* is reached when all of the water has vaporized. The area, 4, under *CD* represents the heat-energy addition necessary to vaporize the water—latent heat of vaporization. Now, as more heat is added to the steam (which is under constant pressure), its temperature increases following the curve, *DE*. The area, 5, under *DE*, represents the heat-energy addition required to superheat the steam at a pressure of 300 lb. per sq. in. to the temperature *E* which is 1,278° F. abs. If more heat energy is added to the steam, the curve *DE* will continue to rise until the steam begins to dissociate into its component elements, hydrogen and oxygen.

379. In Engineering, Only A Portion Of The Complete Temperature-entropy Diagram Is Used, as shown in Fig. 342. Since in engineering we are not concerned with vapors in the solid state only a part of the complete temperature-entropy diagram, which is shown in Fig. 341, is necessary to represent the heat transfers of vapor practice. The part which is most frequently used is that to the right of *BB′* in Fig. 341 or that shown in Fig. 342, that is only that part which concerns temperatures above the melting point.

Explanation.—In both illustrations, (Figs. 341 and 342) the same path is shown: *BCDE*. The area *BCDEE′B′* under this path represents the total heat energy required to change water at 32° F. to highly superheated steam (under a constant pressure of 300 lb. per sq. in. in abs.). This area represents the total heat as given in Steam

Table 395. The line *BHJL* (Fig. 342) represents the temperature-entropy path under a different pressure, 50 lb. per sq. in. abs. When more than one heating process is represented on the temperature-entropy plane, the resulting figure is called a *chart*. Such paths as *BHJL* and *BCDE* are called *constant-pressure lines*. The chart shows that, for different pressures, *the heat of the liquid, the latent heat of vaporization, and the heat required to superheat,* all are different.

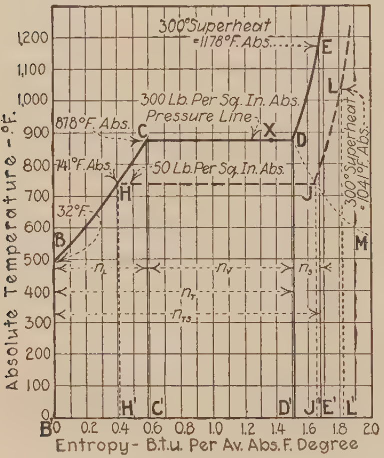


Fig. 342.—Temperature-entropy chart for 1 lb. of steam.

Note.—The Curved Line *DM* Is Called The "Dry Steam Line" (Fig. 342). It connects all points in the various constant-pressure lines which represent dry steam at the various temperatures (pressures). The water line, *BC*, and *DM* would intersect at the critical temperature, if they were extended upward. It should be remembered that this line *DM* is used for convenience to connect dry-saturated-vapor points; strictly, it is not a part of the temperature-entropy diagram and does not represent a physical process.

Note.—The Line *CD* Is Not Only A "Constant Temperature Line" But Is Also A "Constant Pressure Line" (Fig. 342). To the right of the point *D* the constant pressure line is not horizontal but is a rising curve, since at *D* the steam starts to become superheated.

380. The Values For The Entropy Of Vapors At Different Conditions Are Given In The Vapor Tables (Table 394) with the other vapor properties. Besides *the total entropy* there is also usually given *the entropy of the liquid and the entropy of vaporization.* The entropy of the liquid is graphically represented by the distance n_L (Fig. 342) and the entropy of vaporization by the distance n_V, for the given pressure. The *total entropy for dry saturated steam* is represented by the sum of the two or by the distance n_T. The total *entropy of superheated vapors* is given in the tables of superheated vapors (Table 395) and is represented by n_{TS} in Fig. 342. The entropy of superheat (n_S, Fig. 342) for a given degree of superheat can be obtained by subtracting the entropy of dry saturated vapor, which is at the same pressure as the superheated vapor, from that of the superheated vapor.

381. The Total Entropy For A Wet Vapor Cannot Be Obtained Directly From The Vapor Tables.—It can, however, be calculated when the quality of the steam is known by the following formula:

(259) $\mathbf{n}_W = \mathbf{n}_L + \mathbf{x}\mathbf{n}_V$ (B.t.u. per lb. per avg. abs. ° F.)

Wherein: $\mathbf{n}_W$ = total entropy for 1 lb. of wet vapor. $\mathbf{n}_L$ = entropy for 1 lb. of liquid at the same pressure, as taken from the vapor-property table. $\mathbf{n}_V$ = entropy of vaporization for 1 lb. of vapor at the same pressure, as taken from the vapor property table. $\mathbf{x}$ = quality of the vapor expressed decimally. The application of this formula is illustrated in following Probs. 4 and 5, see appendix for solutions.

Derivation.—In any temperature-entropy diagram showing the vaporization of a liquid: *Entropy change of vaporization* = (*Latent heat of vaporization*) ÷ (*Absolute temperature*). Thus in Fig. 342, $\mathbf{n}_V$ = (*Latent heat of vaporization of the dry steam*) ÷ (*Absolute temperature*). When the vapor is wet all of the latent heat of dry steam is not used but the temperature remains the same as that of dry steam. Hence, when the vapor is wet, the entropy change of vaporization will be less than that for dry steam and D will (Fig. 342) move to some point X. Consequently, for wet steam: *The Entropy change, CX* = (*Latent heat of vaporization of wet steam*) ÷ (*Absolute temperature*). Since, as stated above and as is evident from Fig. 342, the "*Absolute temperature*" is the same for both of the two above equations, it is evident that:

(260) $$\frac{CX}{\mathbf{n}_V} = \frac{\textit{Latent heat of the wet steam}}{\textit{Latent heat of the dry steam}}$$

Now (see Sec. 366) if x represents the quality expressed decimally, then:

(261) $$\frac{\textit{Latent heat of the wet steam}}{\textit{Latent heat of the dry steam}} = \mathbf{x}$$

Hence, substituting in For. (260) the equivalent from For. (261) there results:

(262) $$\frac{CX}{\mathbf{n}_V} = \mathbf{x}; \text{ or, } CX = \mathbf{x}\mathbf{n}_V$$

Now, as is evident from Fig. 342, the total entropy change of the wet vapor, which will be here designated by $\mathbf{n}_W$, equals the sum of $\mathbf{n}_L + CX$. That is:

(263) $$\mathbf{n}_W = \mathbf{n}_L + CX$$

Now, substituting in For. (263) the equivalent for CX from For. (262), there results:

(264) $$n_W = n_L + x n_V$$

Which is the same as For. (259).

Note.—The Quality Can Be Determined, If n_T And n_L Are Known.—For, by transposing For. (259), we obtain:

(265) $$x = \frac{n_W - n_L}{n_V} \qquad \text{(decimal.)}$$

This is the relation which is useful in determining the quality of a vapor after a frictionless adiabatic (isentropic) expansion. In a frictionless adiabatic expansion n_W is known and n_L can be found from the vapor tables. The quality can also be obtained directly from the chart of Fig. 343. The application of this formula is illustrated in following Prob. 5; see appendix for solution.

382. The "Temperature-entropy" And The "Mollier" Or "Heat-entropy" Charts Are Graphs Which Show The Principal Properties Of A Vapor; see Fig. 343. Thus, the properties of a vapor can be represented on a graph for which entropy and temperature, or entropy and some other properties are employed as coordinates. These charts are especially useful in frictionless-adiabatic-expansion calculations. The employment of entropy in plotting these charts is, as explained in preceding Sec. 373, its most important practical application. The temperature-entropy chart is merely a combination of many temperature-entropy diagrams as shown in Fig. 341. The Mollier diagram or heat chart (Fig. 343) uses *entropy* and *total heat content* as coordinates and, since in practical computations the total heat-content is generally desired, this is the most frequently used and the more convenient chart. From it the heat content, in British thermal units, can be read off directly. The heat-entropy chart resembles the temperature-entropy chart; it has the same lines only they have a different slope. It is, as is explained below, plotted in a manner similar to that employed for the temperature-entropy chart. In steam practice only the upper right-hand portion of a diagram such as that of Fig. 344 is needed in calculations; therefore, this is the only portion reproduced in the practical charts.

Explanation.—A Heat-entropy Or Mollier Chart May Be Constructed In The Following Manner.—For this chart (Fig. 343), total heat and entropy are the two coordinates used and they should be plotted at right angles. Fig. 344 illustrates the process. The plotted values are from Steam Table 394. When the heat content is zero, the entropy is zero. The usual practice of assuming an arbitrary zero, or datum for heat content and entropy, at 32° F. (Sec. 374) is here followed. Thus, the state of zero entropy and zero heat content starts at

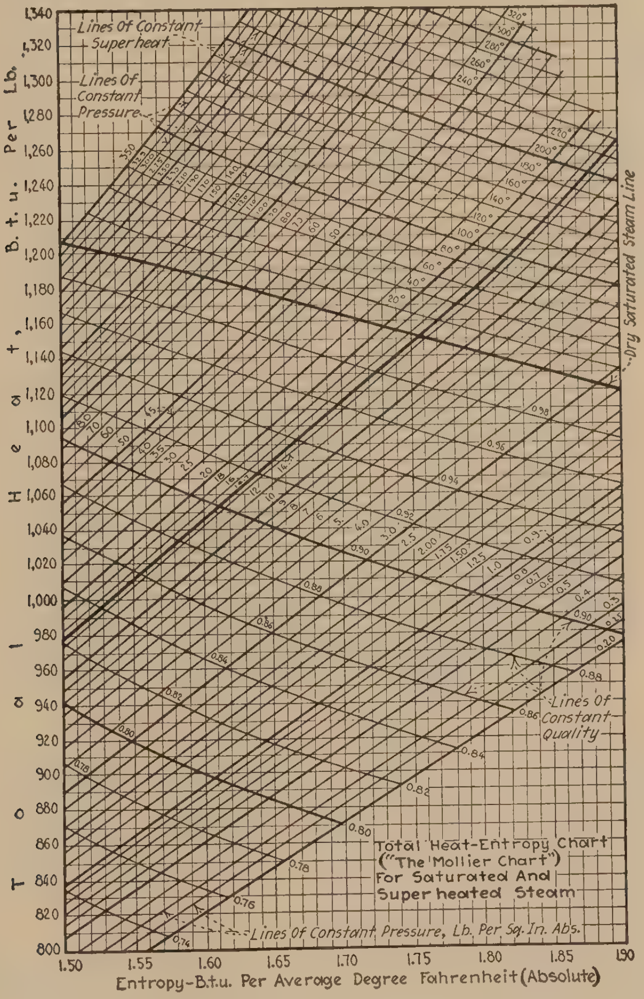


Fig. 343.—Total heat-entropy chart for steam.

O (Fig. 344), with water at 32° F. As heat is applied the entropy increases, the state point moves along the *liquid or water line OA* which is similar to that of the temperature-entropy diagram, BC Fig. 342. This line, OA, is obtained by plotting the heat-of-the-liquid values against the corresponding entropy-of-the-liquid values, as obtained from Steam Table 394 for various pressures. When evaporation begins as at A, the entropy increases in direct proportion to the heat added, so the evaporation line AB is straight. The point B is obtained by plotting the value of the total heat of dry saturated steam at 300 lb. per sq. in. abs. against the value of the corresponding entropy; both values are from Steam Table 394. During superheating, the entropy increases from B to C but not in direct proportion to the heat added, so the line BC, has a slight curvature. The line BC is obtained by plotting the values of the total heat of superheated steam against the corresponding entropy values for various degrees of superheat, but all at 300 lb. per sq. in. abs. pressure. These values are all obtained from Steam Table 395. The path followed $OABC$ is the *line of constant pressure.*

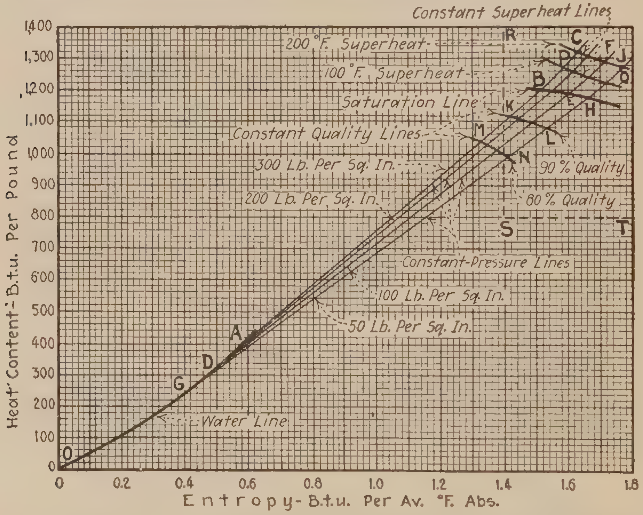


Fig. 344.—Showing how a heat-entropy or Mollier chart for steam is constructed.

Other constant pressure lines may be similarly drawn, such as $ODEF$ and $OGHJ$. The points B, E, and H, which represent dry saturated steam on the various constant-pressure lines, are then connected by the line BH. This line is the 100 per cent. quality line or *saturation line.* It is the dividing line between the wet-steam region, the area below it, and the superheated-steam region, the area above.

The point, K, is chosen on the line AB so that the distance AK, divided by the distance AB equals 0.90; similarly, points are located on the other constant-pressure lines. These points are then connected by the line *KL*, which is the 90 per cent. *constant-quality line.* Other constant quality lines may be drawn, such as *MN*.

Lines connecting points all of which have the same degree of superheat but which are located on the different constant-pressure lines are called *lines of constant superheat.* Such a line for 100° superheat is shown at *PQ*.

Horizontal lines on Fig. 344 represent constant heat content, and vertical lines constant entropy. Frictionless adiabatic (isentropic) processes are represented by the latter (see Sec. 385). The upper right-hand portion of Fig. 344, which is shown cut out by the dotted lines, is all that is reproduced in a practical heat-entropy chart (Fig. 343) because the remaining portion of Fig. 344 would never be used. Lines of constant volume may be, but seldom are, plotted on the same chart with the properties of Fig. 344 because too many lines on one chart make it difficult to read.

383. There Are An Infinite Number Of Ways In Which A Vapor Can Expand Or Be Compressed just as there are an infinite number of ways in which a gas can expand or be compressed (Div. 8). Of this infinite number, only three ideal ways (Fig. 345), a knowledge of which is useful because close approximations of them occur in practical heat phenomena, will be treated here.

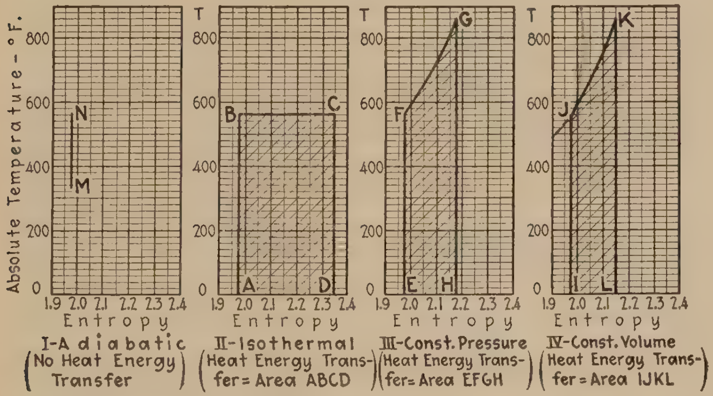


FIG. 345.—Showing characteristic temperature-entropy graphs for adiabatic (isentropic). isothermal, constant-pressure, and constant-volume processes.

NOTE.—IN A SENSE IT MAY BE CONSIDERED THAT THERE ARE ONLY TWO FUNDAMENTAL WAYS IN WHICH A VAPOR OR GAS CAN EXPAND. (1) *Isothermal* or at constant temperature, Fig. 345-*II*. (2) *Isentropic,* Sec. 385 or at constant entropy, Fig. 345-*I*. All other expansions lie somewhere between these two as limits and all others, may in a sense be considered as the simultaneous occurrence of these two in various combinations. The slope of any expansion line, as *FG* (Fig. 345), is determined by the specific heat of the substance under the given conditions.

384. The Expansions Of Vapors, Close Approximations Of Which Ordinarily Occur In Practice are: (1) *Frictionless adiabatic (isentropic) expansion.* (2) *Constant-pressure expansion.* (3) *Constant-heat-content expansion* or *throttling*. These are ideal ways of expansion for various processes and while they are in these certain processes generally closely approximated in practice, they are never actually obtained. The characteristics of these ideal expansions are given in the following sections.

Note.—The Line Of Constant Volume, sometimes called the constant-volume expansion line *JK*, Fig. 345-*IV*, does not really represent an expansion since no change in volume takes place. However the area *IJKL* does represent the heat-energy transfer necessary to raise the temperature of the vapor from *J* to *K* at constant volume. This line, *JK*, is the dividing line between compressions and expansions. Any line drawn through a point, as *J*, so that if falls (no matter what its direction) to the lower right of the constant volume line *JK* represents some expansion process. Likewise any line through *J* falling to the upper left of *JK* represents some compression process. Any number of both such lines are possible for various expansion and compression processes.

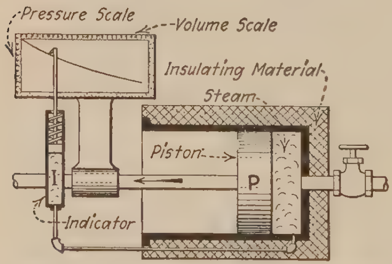


Fig. 346.—Representing an adiabatic isentropic expansion of water vapor—steam. (The expansion is rapid. Work is done by piston *P*. The insulating material prevents transfer of heat, as heat, during the expansion. An indicator, *I*, gives a deflection proportional to the pressure.)

385. An Isentropic Or Frictionless Adiabatic Expansion Of A Vapor is that expansion in which (Fig. 346), the entropy of the vapor remains constant; it is a *constant-entropy expansion.* On a temperature-entropy diagram (or on a heat-entropy diagram), it is represented by a vertical straight line (*MN*, Fig. 345). During this expansion the vapor does mechanical work but receives or gives off no heat energy, as heat, from or to external sources or due to internal friction during the expansion. This expansion corresponds to the frictionless adiabatic expansion of a perfect gas as defined in Sec. 272. An isentropic expansion is often called simply "an adiabatic" expansion, but, strictly speaking, this term is not correct. The term "adiabatic" may mean a whole family of changes in which no heat transfer to or from external objects takes place; the isentropic expansion is but one of these. *The isentropic expansion is generally assumed as the ideal for vapor engines* (Div. 12) because, as shown below, it is the expansion during which the greatest possible amount of the heat energy in a substance at a given temperature is converted into external work. Isentropic expansions are approached in the steam-engine cylinder and in the steam-turbine nozzles.

Explanation.—That the maximum heat energy will be converted into mechanical work by an isentropic adiabatic expansion will be evident by referring to Fig. 347. The line *AB* represents, to scale, the isentropic expansion of 1 cu. ft. of dry saturated steam at 308° F. until its temperature falls to 162° F. By Sec. 262, (Division 8) the shaded area under *AB* represents the work done by the steam during its expansion. Suppose that another expansion, during which heat is abstracted from the steam, is represented by another line *AC*. Then *AC* must fall to the left of *AB* because, at any pressure during the expansion the quality of the steam, and hence the volume, will be less than during the isentropic expansion—because of the extracted heat. Hence the area under any such expansion graph (shaded dark) will be less than that under *AB*—less work will be done than by the isentropic expansion. The only way that the expansion graph could be made to fall to the right of *AB* would be by adding heat during the expansion process. As will be explained (Div. 12), this would be a less efficient process. Therefore, the isentropic expansion is often taken as an "ideal" in heat-engine calculations.

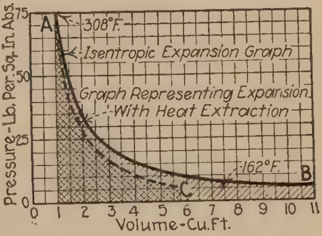


Fig. 347.—Pressure-volume graphs showing that an isentropic expansion extracts (as external work) more heat than any other expansion during which no heat is added to the substance. The graphs are drawn for steam expanding to 162° F. from the dry saturated condition at 308° F.

Note.—The Condition Changes Which Accompany Isentropic Expansions Of Vapors may be read from their temperature-entropy diagrams which show that constant-entropy or isentropic expansion of dry vapor causes wetness; of superheated vapor, causes loss of superheat; and of very wet vapor causes drying. Thus, from Fig. 342, it is evident that the isentropic expansion of dry saturated water vapor (steam) from any pressure, as for example downward along *DD′*, will result in wet steam (Sec. 355). This is because any point below *the saturation line*, *DM*, lies in an area which represents wet steam. It is also similarly evident that the isentropic expansion of superheated steam at any pressure and degree of superheat, such as represented by a path downward along *EE′*, results in a loss of superheat and if the expansion is continued, wet steam will likewise result. For wet steam with a quality less than about 50 per cent., the quality lines (Sec. 382) slope in the same general direction as the water line, *BC*. Hence, if an isentropic expansion starts with very wet steam (a quality of less than about 50 per cent.) drier steam will result. That is, following downward along the line *CC′* (Fig. 342), the quality of the steam increases. *Ether is an exception* to the first two of the above statements in that the isentropic expansion of its dry vapor causes superheat and the isentropic expansion of its superheated vapor causes greater superheat.

Note.—To Determine From The Heat-entrophy Chart, Fig. 343, The Quality Of Steam After Isentropic Expansion, proceed thus. Suppose it is desired to find the quality of superheated steam after isentropic expansion from a pressure of 200 lb. per sq. in. abs. and at 200° F. superheat to a pressure of 1.5 lb. per sq. in. abs. Start at the intersection of the 200 lb. per sq. in. abs. constant pressure and 200° F. superheat lines. Then follow vertically down the constant-entropy line until the 1.5 lb. per sq. in. abs. constant-pressure line is reached. The point thus located is between the 84 and 85 per cent. constant quality lines. The distance between the point and the 84 per cent. constant quality line is about $\frac{2}{5}$ of the total distance between the 84 and 85 per cent. constant-quality lines. Thus the *quality* = $84\frac{2}{5}$ or 84.4 *per cent.*

386. Constant-pressure Expansion (Fig. 345-*III*), as the name implies, is expansion against a constant pressure. This is the expansion that takes place in a boiler when water is vaporized. It also takes place in a superheater where vapor is heated at constant pressure. It occurs in the cooling coil of a refrigerating plant. But the cooling coil in a refrigerating plant is analogous to the boiler and superheater in a steam plant, since in it the liquid absorbs heat from the room or body which is to be cooled.

387. Constant-heat Expansion (Fig. 348) sometimes called "*wire-drawing*" or "*throttling*," as the name implies, means expansion during which the heat-content of the vapor does not change. It occurs when a vapor expands from a high-pressure through a small crack or orifice to a lower pressure so that the only mechanical work done is that expended in overcoming friction. But this friction work merely heats the orifice and surroundings so the heat thereof is reabsorbed by the vapor. Thus the heat content per pound of vapor is the same after expansion as before expansion.

EXAMPLES.—This constant-heat expansion occurs in the throttling calorimeter (Sec. 392). It takes place also to some extent in undersized pipes and partly opened valves. It cannot be used advantageously in engines since in it no heat is converted into work. It is employed in refrigeration (Sec. 632) where the pressure on the refrigerant is lowered by permitting the refrigerant liquid which is under high pressure to expand through an orifice into a space where the pressure is much lower.

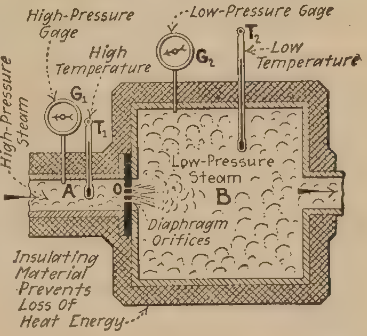


FIG. 348.—Constant-heat or Joule-Thompson expansion, also called wire drawing and throttling. (The steam passes from the high-pressure, G_1, and temperature, T_1, conditions in, A, to the low-pressure, G_2, and temperature, T_2, conditions in B, without loss of heat content.

388. Compression Of Vapors Occurs Ordinarily In One Of Three Ways or in some combination of them: (1) *Isentropic or constant-entropy* compression. (2) *Isodynamic or constant-internal energy* compression. (3) *Constant-pressure compression.* As with the expansion of vapors (Sec. 383) there are an infinite number of ways of compression. *Isentropic compression* is the reverse of isentropic expansion. In it, the largest possible amount of mechanical work is changed into heat energy but no heat is added to or abstracted from the vapor as heat. Thus the internal energy of the vapor is increased. Since in vapor compression it is not desired to change a maximum of mechanical work into heat, but instead to change a minimum of mechanical work into heat, adiabatic compression instead of being an ideal compression is the least desired of all compressions. *Isodynamic compression* is that compression during which the internal energy in the vapor remains constant. This may (theoretically but not practically) be obtained by absorbing heat from the vapor with cooling water at the same rate as the mechanical work is done. It is the ideal compression for refrigerants as the mechanical work done during it in the compression from one state to another is less than that done during any other compression. *Constant-pressure compression* is the reverse of constant-pressure expansion; it is compression or contraction which occurs at constant pressure. This compression takes place in a condenser when a vapor is condensed.

389. The Energy Relations During An Isentropic Process may be found from the following formulas which are derived as shown below. The pressure-volume relations may be computed from values found on the constant-entropy line on the total heat-entropy chart (Fig. 343). The energy relations are:

(266) $\mathbf{Q} = 0$ (heat added)

(267) $\mathbf{Q}_I = \mathbf{I}_2 - \mathbf{I}_1$ (B.t.u. per lb.)

(268) $W_E = 778\,(\mathbf{I}_1 - \mathbf{I}_2)$ (ft.-lb. per lb. of vapor)

(269) $W_E = 778\,(\mathbf{H}_1 - \mathbf{H}_2) + 144(P_2V_2 - P_1V_1)$ (ft.-lb. per lb. of vapor)

Wherein: $\mathbf{Q}$ = the heat added during the process. W_E = the external work done *by* the vapor during the process, in foot-pounds per pound of vapor. $\mathbf{Q}_I$ = the change in internal energy during the process, in British thermal units per pound of vapor. $\mathbf{I}_1$ and $\mathbf{I}_2$ = respectively, the internal energy of the vapor at the beginning and end of the process, in British thermal units per pound. $\mathbf{H}_1$ and $\mathbf{H}_2$ = respectively the heat contents of the vapor at the beginning and end of the process, in British thermal units per pound. P_1 and P_2 = respectively, the pressures of the vapor at the beginning and end of the process, in pounds per square inch absolute. V_1 and V_2 = respectively, the specific volumes of the vapor at the beginning and end of the process, in cubic feet per pound.

Derivation.—Since, by definition, no heat is added to or abstracted from the substance during an isentropic process, For. (266), which expresses this fact mathematically, must hold. Now, by For. (58), for any condition change

(270) $$Q = Q_I + Q_E \qquad \text{(B.t.u.)}$$

Hence, by combining Fors. (266) and (270), there results

(271) $$0 = Q_I + Q_E \qquad \text{(B.t.u.)}$$

or, by transposing

(272) $$Q_E = -Q_I \qquad \text{(B.t.u.)}$$

Now, it is evident that For. (267) expresses the value of Q_I. Hence, by combining Fors. (267) and (272), there results:

(273) $$Q_E = -(I_2 - I_1) = I_1 - I_2 \qquad \text{(B.t.u.)}$$

But, by For. (46), $W_E = 778\ Q_E$. Hence:

(274) $$W_E = 778\ (I_1 - I_2) \qquad \text{(ft.-lb.)}$$

Now, For. (249) gives the expressions for I_1 and I_2 which, when substituted in For. (274), give For. (269).

EXAMPLE.—How much work is done by 1 lb. of steam in a steam-engine cylinder during its expansion from 150 lb. per sq. in. gage (dry saturated) to 29.3 lb. per sq. in. gage? Assume that the expansion is isentropic. SOLUTION.—From Table 394, for 150 lb. per sq. in. gage: H_D = 1,195.0 B.t.u. per lb.; n_D = 1.561,5; V_D = 2.753 cu. ft. per lb. Also, for 29.3 lb. per sq. in. gage: h = 242.0 B.t.u. per lb.; L = 929.2 B.t.u. per lb.; n_L = 0.400,2; n_V = 1.268,1; V_D = 9.59 cu. ft. per lb. Now, since the entropy remains constant, the *quality* after expansion may be determined by For. (265), thus: $x = (n_W - n_L)/n_V$ = (1.561,5 − 0.400,2) ÷ 1.268,1 = 0.916. Hence, by For. (242), the *total heat* after expansion = $H_W = h + xL$ = 242.0 + (0.916 + 929.2) = 1,093 *B.t.u. per lb.* Also by For. (245), the *specific volume* after expansion = $V_W = xV_D$ = 0.916 × 9.59 = 8.78 *cu. ft. per. lb.* Now, by For. (269), the *work done* = $W_E = 778\ (H_1 - H_2) + 144\ (P_2V_2 - P_1V_1)$ = 778 × (1,195 − 1,093) + {144 × [(44 × 8.78) − (164.7 × 2.753)]} = 793,500 − 96,800 = 696,700 *ft.-lb.*

EXAMPLE.—How much work is done on 1 lb. of ammonia vapor of quality 0.80 and at 30 lb. per sq. in. abs. in compressing it isentropically to ¼ its volume? SOLUTION.—Values for the several properties are taken from Table 399. By For. (259), the *entropy* = $n_W = n_L + xn_V$ = −0.070,9 + (0.80 × 1.244,9) = 0.925,0. By For. (245), the *specific volume before compression* = $V_W = xV_D$ = 0.80 × 9.19 = 7.35 *cu. ft. per lb.* Hence, the *specific volume after compression* = $V_2 = V_1/4$ = 7.35 ÷ 4 = 1.838 *cu. ft. per lb.* By trial, using Fors. (247) and (259), it is found that a specific volume of 1.838 cu. ft. per lb. corresponds at at 80° F. to a quality of 0.949 and an entropy of 0.987,5; at 75° F. to a quality of 0.872 and an entropy of 0.921,0. Hence, the *temperature after compression* = 75 + 5 [(0.925,0 − 0.921,0) ÷ (0.987,5 − 0.921,0)] = 75.3° F. Likewise, the *quality after compression* = 0.877 and the *pressure after compression* = 142 *lb. per sq. in. abs.* Hence, the *total heat after compression*, by For. (242), = $H_W = h + xL$ = 48.3 + (0.877 × 507.8) = 493 *B.t.u. per lb.* Likewise, the *total heat before compression* = $H_W = h + xL$ = −33.7 + (0.80 × 572.2) = 414.1 *B.t.u. per lb.* Therefore, by For. (269), the *work done* $= W_E = 778\ (\mathbf{H}_1 - \mathbf{H}_2) + 144\ (P_2V_2 - P_1V_1) = 778 \times (414.1 - 493) + 144\ [(142 \times 1.838) - (30 \times 7.35)] = -61{,}380 + 5{,}832 = -55{,}548$ *ft.-lb.* Hence, the *work done on the vapor* = 55,548 *ft.-lb.*

390. The Energy Relations During A Constant-pressure Process are quite simple. Since total heats, Secs. 365 to 367, represent heat additions at constant pressure they represent constant-pressure processes. Therefore, for constant-pressure processes the following formulas may be written:

(275) $\mathbf{Q} = \mathbf{H}_2 - \mathbf{H}_1$ (B.t.u. per lb.)

(276) $\mathbf{Q}_I = \mathbf{I}_2 - \mathbf{I}_1$ (B.t.u. per lb.)

(277) $W_E = 144\ P\ (V_2 - V_1)$ (ft.-lb. per lb.)

Wherein: $\mathbf{Q}$ = the heat added to the substance, in British thermal units per pound. $\mathbf{Q}_I$ = the change in internal energy during the process, in British thermal units per pound. W_E = the external work done *by* each pound of vapor, in foot-pounds. $\mathbf{H}_1$ and $\mathbf{H}_2$ = the total heats, respectively, at the beginning and end of the process, in British thermal units per pound. $\mathbf{I}_1$ and $\mathbf{I}_2$ = respectively, the initial and final values of the internal energy of the vapor, in British thermal units per pound. P = the pressure of the vapor, in pounds per square inch absolute. V_1 and V_2 = the initial and final specific volumes of the vapor, respectively, in cubic feet per pound.

EXAMPLE.—How much work is done by 1 lb. of steam as it evaporates in a boiler at 350° F. and is superheated to 500° F.? How much heat is added? SOLUTION.—From Table 393, the specific volume of water at 350° F. is 0.018 *cu. ft. per lb.* From Table 395, by interpolating, the volume of 1 lb. of superheated steam at 134.6 lb. per sq. in. abs. and 150° F. superheat is 4.15 *cu. ft. per lb.* Hence, by For. (277), the *external work* $= W_E = 144\,P(V_2 - V_1) = 144 \times 134.6 \times (4.15 - 0.018) = 80{,}000$ *ft.-lb.* Also, the total heat of the superheated steam is $\mathbf{H}_S = 1{,}272.2$ *B.t.u. per lb.* and, the heat of the liquid at 350° F. is 321.4 *B.t.u. per lb.* Hence, by For. (275), the *heat* added $= \mathbf{H}_2 - \mathbf{H}_1 = 1{,}272.2 - 321.4 = 950.8$ *B.t.u. per lb.*

EXAMPLE.—How much heat must be abstracted from 1 lb. of dry saturated ammonia at 85° F. in condensing it to the liquid state and how much external work is done by the ammonia in condensing? SOLUTION.—By Table 299, $P = 167.4$ *lb. per sq. in. abs.* $V_D = 1.788$ *cu. ft. per lb.* $V_L = 0.027$ cu. ft. per lb. $\mathbf{H}_D = 557.9$ *B.t.u. per lb.* $\mathbf{h} = 59.4$

B.t.u. per lb. Hence, by For. (275), the *heat added* = $\mathbf{Q} = \mathbf{H}_2 - \mathbf{H}_1 = 59.4 - 557.9 = -498.5$ *B.t.u. per lb.*; or, the *heat abstracted* = $-\mathbf{Q} = 498.5$ *B.t.u. per lb.* Also, by For. (277), the *work done by the vapor* = $W_E = 144P(V_2 - V_1) = 144 \times 167.4 \times (0.027 - 1.788) = -42{,}450$ *ft. lb.*; or, the *work done on* the vapor = $-W_E = 42{,}450$ *ft.-lb.*

Note.—The Energy Relations During Throttling And Isodynamic Processes are not required in engineering work. For a throttling process, as explained in Sec. 387, $\mathbf{Q} = 0$, $W_E = 0$, and, therefore, $\mathbf{Q}_I = 0$. For an isodynamic process, by definition, $\mathbf{Q}_I = 0$; hence $\mathbf{Q} = -W_E/778$.

391. The Characteristics Of Water Vapor—Steam—Make It The Best Medium Of All The Vapors For Transforming Heat Energy Into Mechanical Work.—The water from which it is formed is the cheapest and most plentiful of all liquids.

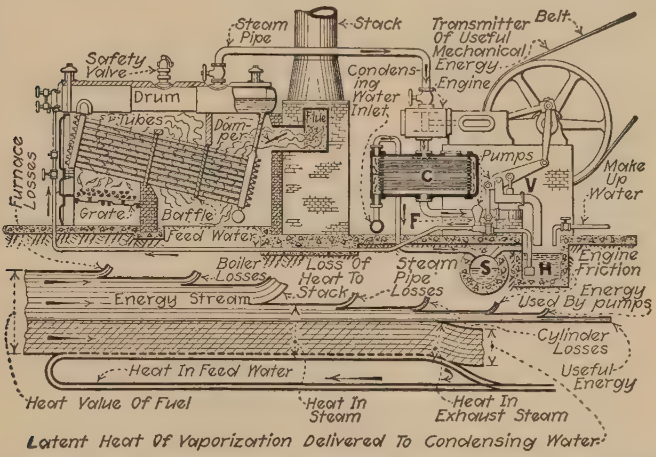


Fig. 349.—Latent heat of vaporization in steam-engine operation. (C = condenser. H = hot well. S = sewer. V = vacuum pump. F = feed pump.)

It is relatively non-corrosive and does not harm the interiors of boilers. The steam formed does not attack steel. It gives off no fumes that are harmful to the body. Another important property is that the water has a large latent heat of vaporization (see Sec. 323), almost twice that of any other vapor. This property of water makes it possible to transmit much heat (Fig. 349) with little liquid or vapor. The boiling temperatures of steam are fairly high with moderate pressures and since the efficiency of an engine depends on the temperature range through which it acts, this is a decided advantage. It is these characteristics of steam which have made it the one vapor used in preference to all others, for generating power.

NOTE.—DRY SATURATED OR SUPERHEATED STEAM IS COLORLESS AND TRANSPARENT as are the colorless gases. The fog (Sec. 343) which one sees issuing from a steam exhaust pipe or from the mouth of a person in winter is really not steam. It is merely condensed water vapor—small particles of water—suspended for the moment in the atmosphere.

392. The Quality Of Steam Can Be Determined By Means Of A Throttling Calorimeter (Figs. 350 and 351), providing the steam is not very wet—the lowest quality determinable by

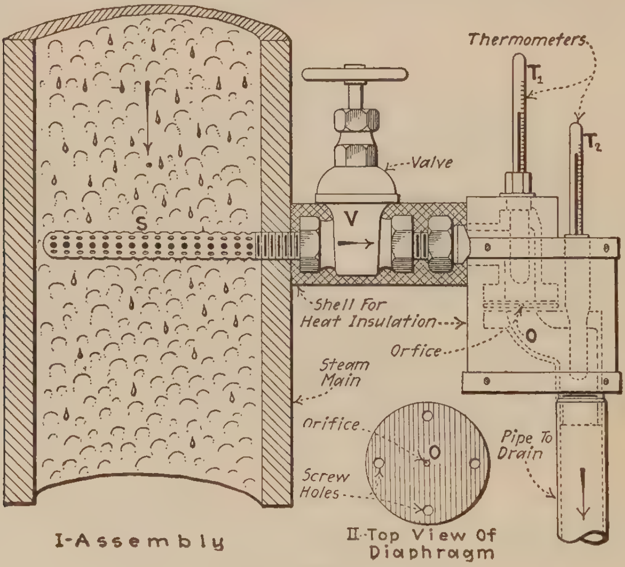


FIG. 350.—Barrus throttling steam calorimeter.

a throttling calorimeter ranges from about 94 per cent. at 300 lb. per sq. in. abs. to about 96.5 per cent. at 100 lb. per sq. in. abs. In plants using saturated steam, it is desirable to know the quality of the steam because the pressure alone does not determine its heat content. When a throttling calorimeter is used, a sample of the steam is obtained by means of a sampling tube, *S* (Fig. 350), extending almost across the steam main in which it is desired to determine the quality. The sampling tube has a uniform arrangement of small holes so that a representative sample is obtained. The admission of the sample is controlled by valve, *V*. The temperature of the incoming steam is measured by a thermometer T_1. The steam then passes through a small hole or orifice, *O*, in the center of a circular plate, into the chamber, *C*, (Fig. 351). The orifice is so small (about 1⁄16 in. in diameter) that the steam pressure is reduced by it to practically atmospheric pressure. The pressure, P_2, in *C* may be measured by a manometer, not shown, but it is generally only slightly more than atmospheric. The calorimeter is thoroughly lagged and, neglecting the small atmospheric rabiation loss, all the heat in the incoming steam, since no work is done by it, must be in the exhaust steam. Since the heat content of slightly wet steam at higher pressures is greater than that of saturated steam at atmospheric pressure, the exhaust steam will be superheated. When the calorimeter is in use, *V* is opened wide and the temperature of the exhaust is read from the thermometer T_2.

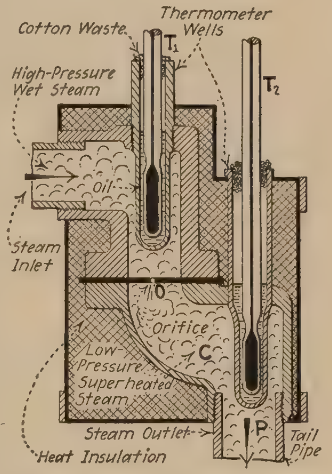


FIG. 351.—Section of Barrus throttling calorimeter in operation.

393. Table Showing Density and Specific Volume Of Water At Different Temperatures.—Abridged from "Steam Tables" by Marks and Davis (Longmans).

Temperature, deg. Fahr.	Specific volume, cu. ft. per lb.	Density, lb. per cu. ft.	Temperature, deg. Fahr.	Specific volume, cu. ft. per lb.	Density, lb. per cu. ft.
40	0.01602	62.43	210	0.01670	59.88
70	0.01605	62.30	250	0.01700	58.83
100	0.01613	62.00	300	0.01744	57.33
130	0.01625	61.55	350	0.01800	55.57
170	0.01645	60.80	400	0.0187	53.5

394. Table Giving The Properties Of 1 lb. Of Dry Saturated Steam. (Based on data by L. S. Marks and H. N. Davis, Longmans Green and Co.)

Pressure		Temperature, deg. Fahr.	Heat—British thermal units					Entropy (a ratio) B.t.u. per average abs. F. degree			Specific volume, cu. ft. per lb.	Density, lb. per cu. ft.
Inches of mercury abs.	Lb. per sq. in. abs.		Total of steam	Of liquid (water)	Latent			Total	Of liquid	Of vaporization		
					Total	Internal	External					
(1) P_M	(2) P	(3) T	(4) H_D	(5) h	(6) L	(7) L_I	(8) L_F	(9) n_D	(10) n_L	(11) n_V	(12) V_D	(13) D
0.1804	0.0886	32	1,073.4	0.0	1,073.4	1,019.3	54.1	2.1832	0.0000	2.1832	3,294.0	0.0003
0.502	0.2472	59	1,085.4	27.08	1,058.3	1,001.3	57.0	2.0944	0.0536	2.0408	1,249.2	0.0008
0.99	0.4893	79	1,094.3	47.04	1,047.3	988.1	59.2	2,0358	0.0913	1.9445	657.0	0.0015
1.50	0.741	92	1,100.1	60.0	1,040.0	979.4	60.6	2.0007	0.1151	1.8856	442.2	0.0023
1.98	0.975	101	1,104.0	68.97	1,035.1	973.5	61.6	1.9776	0.1313	1.8463	341.0	0.0029
2.51	1.235	109	1,107.5	76.94	1,030.6	968.2	62.4	1.9678	0.1454	1.8124	272.9	0.0037
2.98	1.467	115	1,110.2	82.92	1,027.2	964.2	63.0	1.9435	0.1559	1.7876	231.9	0.0043
3.52	1.736	121	1,112.8	88.91	1,023.9	960.2	63.7	1.9296	0.1662	1.7634	197.9	0.0051
4.04	1.992	126	1,115.0	93.90	1,021.1	956.8	64.3	1.9183	0.1747	1.7436	173.9	0.0058
4.50	2.219	130	1,116.7	97.89	1,018.8	954.1	65.1	1.9095	0.1816	1.7279	157.1	0.0064
5.01	2.467	134	1,118.4	101.88	1,016.5	951.4	65.1	1.9008	0.1883	1.7125	142.2	0.0070
	1	101.83	1,104.4	69.8	1,034.6	972.9	61.7	1.9754	0.1327	1.8427	333.0	0.0030
	2	126.15	1,115.0	94.0	1,021.0	956.7	64.3	1.9180	0.1749	1.7431	173.5	0.0058
	3	141.52	1,121.6	109.4	1,012.3	946.4	65.9	1.8848	0.2008	1.6840	118.5	0.0085
	4	153.01	1,126.5	120.9	1,005.7	938.6	67.1	1.8614	0.2198	1.6416	90.5	0.0111
	5	162.28	1,130.5	130.1	1,000.3	932.4	67.9	1.8432	0.2348	1.6084	73.33	0.0136
	6	170.06	1,133.7	137.9	995.8	927.0	68.8	1.8285	0.2471	1.5814	61.89	0.0162
	7	176.85	1,136.5	144.7	991.8	922.4	69.4	1.8161	0.2579	1.5582	53.56	0.0187
	8	182.86	1,139.0	150.8	998.2	918.2	70.0	1.8053	0.2673	1.5380	47.27	0.0212
	9	188.27	1,141.1	156.2	985.0	914.4	70.6	1.7958	0.2756	1.5202	42.36	0.0236
	10	193.22	1,143.1	161.1	982.0	910.9	71.1	1.7874	0.2832	1.5042	38.38	0.0261

Ld. per sq. in. gage	11	197.75	1,144.9	165.7	979.2	907.8	71.4	1.7797	0.2902	1.4895	35.10	0.0285
	12	201.96	1,146.5	169.9	976.6	904.8	71.8	1.7727	0.2967	1.4760	32.36	0.0309
P_G	13	205.87	1,148.0	173.8	974.2	902.0	72.2	1.7664	0.3025	1.4639	30.03	0.0333
	14	209.55	1,149.4	177.5	971.9	899.3	72.6	1.7604	0.3081	1.4523	28.02	0.0357
0	14.7	212.00	1,150.4	180.0	970.4	897.6	72.8	1.7565	0.3118	1.4447	26.79	0.0373
0.3	15	213.0	1,150.7	181.0	969.7	896.8	72.9	1.7549	0.3133	1.4416	26.27	0.0381
1.3	16	216.3	1,152.0	184.4	967.6	894.4	73.2	1.7494	0.3183	1.4311	24.79	0.0404
2.3	17	219.4	1,153.1	187.5	965.6	892.1	73.5	1.7444	0.3229	1.4215	23.38	0.0423
3.3	18	222.4	1,154.2	190.5	963.7	889.9	73.8	1.7400	0.3273	1.4127	22.16	0.0451
4.3	19	225.2	1,155.2	193.4	961.8	887.8	74.0	1.7360	0.3315	1.4045	21.07	0.0475
5.3	20	228.0	1,156.2	196.1	960.0	885.8	74.2	1.7320	0.3355	1.3965	20.08	0.0498
6.3	21	230.6	1,157.1	198.8	958.3	883.9	74.4	1.7280	0.3393	1.3887	19.18	0.0521
7.3	22	233.1	1,158.0	201.3	956.7	882.0	74.7	1.7241	0.3430	1.3811	18.37	0.0545
8.3	23	235.5	1,158.8	203.8	955.1	880.2	74.9	1.7204	0.3465	1.3739	17.62	0.0568
9.3	24	237.8	1,159.6	206.1	953.5	878.5	75.0	1.7169	0.3499	1.3670	16.93	0.0591
10.3	25	240.1	1,160.4	208.4	952.0	876.8	75.2	1.7136	0.3532	1.3604	16.30	0.0614
11.3	26	242.2	1,161.2	210.6	950.6	875.1	75.5	1.7106	0.3564	1.3542	15.72	0.0636
12.3	27	244.4	1,161.9	212.7	949.2	873.5	75.7	1.7077	0.3594	1.3483	15.18	0.0659
13.3	28	246.4	1,162.6	214.8	947.8	872.0	75.8	1.7048	0.3623	1.3425	14.67	0.0682
14.3	29	248.4	1,163.2	216.8	946.4	870.5	75.9	1.7019	0.3652	1.3367	14.19	0.0705
15.3	30	250.3	1,163.9	218.8	945.1	869.0	76.1	1.6991	0.3680	1.3311	13.74	0.0728
17.3	32	254.1	1,165.1	222.6	942.5	866.2	76.3	1.6938	0.3733	1.3205	12.93	0.0773
19.3	34	257.6	1,166.3	226.2	940.1	863.4	76.7	1.6891	0.3784	1.3107	12.22	0.0818
21.3	36	261.0	1,167.3	229.6	937.7	860.8	76.9	1.6846	0.3832	1.3014	11.58	0.0863
23.3	38	264.2	1,168.4	232.9	935.5	858.3	77.2	1.6802	0.3877	1.2925	11.01	0.0908
25.3	40	267.3	1,169.4	236.1	933.3	855.9	77.4	1.6761	0.3920	1.2841	10.49	0.0953
27.3	42	270.2	1,170.3	239.1	931.2	853.6	77.6	1.6721	0.3962	1.2759	10.02	0.0998
29.3	44	273.1	1,171.2	242.0	929.2	851.3	77.9	1.6683	0.4002	1.2681	9.59	0.1043
31.3	46	275.8	1,172.0	244.8	927.2	849.2	78.0	1.6647	0.4040	1.2607	9.20	0.1087
33.3	48	278.5	1,172.8	247.5	925.3	847.1	78.2	1.6613	0.4077	1.2536	8.84	0.1131
35.3	50	281.0	1,173.6	250.1	923.5	845.0	78.5	1.6581	0.4113	1.2418	8.51	0.1175
37.3	52	283.5	1,174.3	252.6	921.7	843.1	78.6	1.6549	0.4147	1.2402	8.20	0.1219
39.3	54	285.9	1,175.0	255.1	919.9	841.1	78.8	1.6519	0.4180	1.2339	7.91	0.1263
41.3	56	288.2	1,1 5.7	257.5	918.2	839.3	78.9	1.6490	0.4212	1.2278	7.65	0.1307
43.3	58	290.5	1,176.4	259.8	916.5	837.4	79.1	1.6460	0.4242	1.2218	7.40	0.1350
45.3	60	292.7	1,177.0	262.1	914.9	835.6	79.3	1.6432	0.4272	1.2160	7.17	0.1394

394. *Cont'd.* Table Giving the Properties of 1 lb. Of Dry Saturated Steam.

Pressure		Temperature, deg. Fahr.	Heat—British thermal units					Entropy (a ratio) B.t.u per average abs. F. degree			Specific volume, cu. ft. per lb.	Density, lb. per cu. ft.
Inches of mercury abs.	Lb. per sq. in. abs.		Total of steam	Of liquid (water)	Latent			Total	Of liquid	Of vaporization		
					Total	Internal	External					
(1) P_G	(2) P	(3) T	(4) H_D''	(5) h	(6) L	(7) L_I	(8) L_E	(9) n_D	(10) n_L	(11)	(12) V_D	(13) D
47.3	62	294.9	1,177.6	264.3	913.3	833.9	79.4	1.6406	0.4302	1.2104	6.95	0.1438
49.3	64	297.0	1,178.2	266.4	911.8	832.2	79.6	1.6380	0.4330	1.2050	6.75	0.1482
51.3	66	299.0	1,178.8	268.5	910.2	830.5	79.7	1.6355	0.4358	1.2007	6.56	0.1525
53.3	68	301.0	1,179.3	270.6	908.7	828.9	79.8	1.6331	0.4385	1.1946	6.38	0.1569
55.3	70	302.9	1,179.8	272.6	907.2	827.3	79.9	1.6307	0.4411	1.1896	6.20	0.1612
57.3	72	304.8	1,180.4	274.5	905.8	825.8	80.0	1.6285	0.4437	1.1848	6.04	0.1656
59.3	74	306.7	1,180.9	276.5	904.4	824.2	80.2	1.6263	0.4462	1.1810	5.89	0.1699
61.3	76	308.5	1,181.4	278.3	903.0	822.7	80.3	1.6242	0.4487	1.1755	5.74	0.1743
63.3	78	310.3	1,181.8	280.2	901.7	821.3	80.4	1.6221	0.4511	1.1710	5.60	0.1786
65.3	80	312.0	1,182.3	282.0	900.3	819.8	80.5	1.6200	0.4535	1.1665	5.47	0.1829
67.3	82	313.8	1,182.8	283.8	899.0	818.4	80.6	1.6180	0.4557	1.1623	5.34	0.1873
69.3	84	315.4	1,183.2	285.5	897.7	817.0	80.7	1.6160	0.4579	1.1581	5.22	0.1915
71.3	86	317.1	1.183.6	287.2	896.4	815.6	80.8	1.6141	0.4601	1.1540	5.10	0.1959
73.3	88	318.7	1.184.0	288.9	895.2	814.3	80.9	1.6123	0.4623	1.1500	5.60	0.2001
75.3	90	320.3	1.184.4	290.5	893.9	813.0	80.9	1.6105	0.4644	1.1461	4.89	0.2044
77.3	92	321.8	1,184.8	292.1	892.7	811.7	81.0	1.6087	0.4664	1.1423	4.79	0.2087
79.3	94	323.4	1,185.2	293.7	891.5	810.4	81.1	1.6069	0.4684	1.1385	4.69	0.2130
81.3	96	324.9	1,185.6	295.3	890.3	809.1	81.2	1.6052	0.4704	1.1348	4.60	0.2172
83.3	98	326.4	1,186.0	296.8	889.2	807.9	81.3	1.6036	0.4724	1.1312	4.51	0.2215
85.3	100	327.8	1,186.3	298.3	888.0	806.6	81.4	1.6020	0.4743	1.1277	4.429	0.2258

90.3	105	331.4	1,187.2	302.0	885.2	803.6	81.6	1.5980	0.4789	1.1191	4.230	0.2365
95.3	110	334.8	1,188.0	305.5	882.5	800.7	81.8	1.5942	0.4834	1.1108	4.047	0.2472
100	115	338.1	1,188.8	309.0	879.8	797.9	81.9	1.5907	0.4877	1.1030	3.880	0.2577
105	120	341.3	1,189.6	312.3	877.2	795.2	82.0	1.5873	0.4919	1.0954	3.726	0.2683
110	125	344.4	1,190.3	315.5	874.7	792.6	82.1	1.5839	0.4959	1.0880	3.583	0.2991
115	130	347.4	1,191.0	318.6	872.3	790.0	82.3	1.5807	0.4998	1.0809	3.452	0.2997
120	135	350.3	1,191.6	321.7	869.9	787.5	82.4	1.5777	0.5035	1.0742	3.331	0.3002
125	140	353.1	1,192.2	324.6	867.6	785.0	82.6	1.5747	0.5072	1.0675	3.219	0.3107
130	145	355.8	1,192.8	327.4	865.4	782.7	82.7	1.5719	0.5107	1.0612	3.112	0.3213
135	150	358.5	1,193.4	330.2	863.2	780.4	82.8	1.5692	0.5142	1.0550	3.012	0.3320
140	155	361.0	1,194.0	332.9	861.0	778.1	82.9	1.5664	0.5175	1.0489	2.920	0.3425
145	160	363.6	1,194.5	335.6	858.8	775.8	83.0	1.5639	0.5208	1.0431	2.834	0.3529
150	165	366.0	1,195.0	338.2	856.8	773.6	83.2	1.5615	0.5239	1.0376	2.753	0.3633
155	170	368.5	1,195.4	340.7	854.7	771.5	83.2	1.5590	0.5269	1.0321	2.675	0.3738
160	175	370.8	1,195.9	343.2	852.7	769.4	83.3	1.5567	0.5299	1.0268	2.602	0.3843
165	180	373.1	1,196.4	345.6	850.8	767.4	83.4	1.5543	0.5328	1.0215	2.533	0.3948
170	185	375.4	1,196.8	348.0	848.8	765.4	83.4	1.5520	0.5356	1.0164	2.468	0.4052
175	190	377.6	1,197.3	350.4	846.9	763.4	83.5	1.5498	0.5384	1.0114	2.406	0.4157
180	195	379.8	1,197.7	352.7	845.0	761.4	83.6	1.5476	0.5410	1.0066	2.346	0.4262
185	200	381.9	1,198.1	354.9	843.2	759.5	83.7	1.5456	0.5437	1.0019	2.290	0.437
190	205	384.0	1,198.5	357.1	841.4	757.6	83.8	1.5436	0.5463	0.9973	2.237	0.447
195	210	386.0	1,198.8	359.2	839.6	755.8	83.8	1.5416	0.5488	0.9928	2.187	0.457
200	215	388.0	1,199.2	361.4	837.9	754.0	83.9	1.5398	0.5513	0.9885	2.138	0.468
205	220	389.9	1,199.6	363.4	836.2	752.3	83.9	1.5379	0.5538	0.9841	2.091	0.478
210	225	391.9	1,199.9	365.5	834.4	750.5	83.9	1.5361	0.5562	0.9799	2.046	0.489
215	230	393.8	1,200.2	367.5	832.8	748.8	84.0	1.5344	0.5586	0.9758	2.004	0.499
220	235	395.6	1,200.6	369.4	831.1	747.0	84.1	1.5327	0.5610	0.9717	1.964	0.509
225	240	397.4	1,200.9	371.4	829.5	745.4	84.1	1.5309	0.5633	0.9676	1.924	0.520
230	245	399.3	1,201.2	373.3	827.9	743.7	84.2	1.5293	0.5655	0.9638	1.887	0.530
235	250	401.1	1,201.5	375.2	826.3	742.0	84.3	1.5276	0.5676	0.960	1.850	0.541
255	270	409.7	1,202.6	382.5	820.1	735.8	84.3	1.5214	0.5760	0.9454	1.718	0.582
285	300	417.5	1,204.1	392.7	811.3	726.8	84.5	1.5129	0.5878	0.925	1.551	0.645
385	400	444.8	1,208.	422.	786.0	701.	85.	1.489	0.621	0.868	1.17	0.86
485	500	467.3	1,210.	448.	762.	678.	84.	1.470	0.648	0.822	0.93	1.08
. . .	1,000	544.8	1,200.	535.	665.	587.	78.	1.39	0.737	0.668	0.46	2.18
. . .	2,000	636.0			511.	444.	67.			0.446	0.21	4.9
Crit.	3,200	706.1			000.	000.	00.			0.000	0.05	20.1

395. Table Giving The Properties Of 1 lb. Of Superheated Steam (condensed from Marks and Davis' "Steam Tables and Diagrams").

Pressure, lb. per sq. in. abs.	Temp. of saturated steam, deg. Fahr.	Property	Superheat, degrees Fahrenheit								
			20	40	60	80	100	150	200	250	300
20	228.0	V_s	20.73	21.37	22.01	22.63	23.25	24.80	26.33	27.85	29.37
		H_s	1,165.7	1,175.2	1,184.6	1,194.1	1,203.5	1,227.1	1,250.6	1,274.1	1,297.6
		n_s	1.7456	1.7587	1.7716	1.7840	1.7961	1.8251	1.8524	1.8781	1.9026
40	267.3	V_s	10.83	11.16	11.50	11.82	12.13	12.93	13.70	14.48	15.25
		H_s	1,179.3	1,189.1	1,198.9	1,208.7	1,218.4	1,242.4	1,266.4	1,290.3	1,314.1
		n_s	1.6895	1.7025	1.7151	1.7273	1.7392	1.7674	1.7940	1.8189	1.8427
60	292.7	V_s	7.40	7.63	7.86	8.08	8.30	8.84	9.36	9.89	10.41
		H_s	1,187.3	1,197.5	1,207.7	1,217.7	1,227.6	1,252.1	1,276.4	1,300.4	1,324.3
		n_s	1.6568	1.6698	1.6823	1.6944	1.7062	1.7342	1.7603	1.7849	1.8081
80	312.0	V_s	5.65	5.83	6.00	6.18	6.34	6.75	7.17	7.56	7.95
		H_s	1,193.0	1,203.6	1,214.0	1,224.2	1,234.3	1,259.0	1,283.6	1,307.8	1,331.9
		n_s	1.6338	1.6469	1.6594	1.6716	1.6833	1.7110	1.7368	1.7612	1.7840
100	327.8	V_s	4.58	4.72	4.86	5.00	5.14	5.47	5.80	6.12	6.44
		H_s	1197.5	1,208.4	1,219.1	1,229.5	1,239.7	1,264.7	1,289.4	1,313.6	1,337.8
		n_s	1.6160	1.6294	1.6420	1.6541	1.6658	1.6933	1.7188	1.7428	1.7656
120	341.3	V_s	3.85	3.98	4.10	4.22	4.33	4.62	4.89	5.17	5.44
		H_s	1,201.1	1,212.4	1,223.3	1,233.8	1,244.1	1,269.3	1,294.1	1,318.4	1,342.7
		n_s	1.6016	1.6152	1.6279	1.6400	1.6517	1.6789	1.7041	1.7280	1.7505
140	353.1	V_s	3.32	3.44	3.54	3.65	3.75	4.00	4.24	4.48	4.71
		H_s	1,204.3	1,215.8	1,226.8	1,237.5	1,248.0	1,273.3	1,298.2	1,322.6	1,346.9
		n_s	1.5894	1.6031	1.6159	1.6280	1.6395	1.6666	1.6916	1.7152	1.7376

160	363.6	V_s	2.93	3.03	3.12	3.21	3.30	3.53	3.74	3.95	4.15
		H_s	1,207.0	1,218.8	1,230.0	1,240.8	1,251.3	1,276.8	1,310.7	1,326.2	1,350.6
		n_s	1.5789	1.5928	1.6056	1.6177	1.6292	1.6561	1.6810	1.7043	1.7266
180	373.1	V_s	2.62	2.71	2.80	2.81	2.96	3.16	3.35	3.54	3.72
		H_s	1,209.4	1,221.5	1,232.8	1,243.8	1,254.3	1,279.9	1,304.8	1,329.5	1,353.9
		n_s	1.5697	1.5838	1.5767	1.6088	1.6201	1.6468	1.6706	1.6948	1.7169
200	381.9	V_s	2.37	2.45	2.53	2.61	2.68	2.86	3.04	3.21	3.38
		H_s	1,211.6	1,223.9	1,235.5	1,246.5	1,257.1	1,282.6	1,307.7	1,332.4	1,357.0
		n_s	1.5614	1.5757	1.5886	1.6007	1.6120	1.6358	1.6632	1.6862	1.7082
220	389.9	V_s	2.16	2.24	2.31	2.38	2.45	2.62	2.78	2.94	3.10
		H_s	1,213.6	1,226.2	1,237.9	1,248.9	1,259.6	1,285.2	1,310.3	1,335.1	1,359.8
		n_s	1.5541	1.5686	1.5816	1.5936	1.6049	1.6312	1.6558	1.6787	1.7005
240	397.4	V_s	1.99	2.06	2.13	2.20	2.26	2.42	2.57	2.71	2.85
		H_s	1,215.4	1,228.3	1,240.1	1,251.3	1,261.9	1,287.6	1,312.8	1,337.6	1,362.3
		n_s	1.5476	1.5623	1.5753	1.5873	1.5985	1.6246	1.6492	1.6720	1.6937
260	404.5	V_s	1.84	1.91	1.97	2.04	2.10	2.24	2.39	2.52	2.65
		H_s	1,217.1	1,230.3	1,242.3	1,253.4	1,264.1	1,289.9	1,315.1	1,340.0	1,364.7
		n_s	1.5416	1.5564	1.5695	1.5815	1.5926	1.6186	1.6430	1.6658	1.6874
280	411.2	V_s	1.72	1.78	1.84	1.90	1.95	2.09	2.22	2.35	2.98
		H_s	1,218.7	1,232.2	1,244.3	1,255.5	1,266.2	1,291.9	1,317.2	1,342.2	1,367.0
		n_s	1.5362	1.5512	1.5643	1.5762	1.5873	1.6133	1.6375	1.6603	1.6818
300	417.5	V_s	1.60	1.66	1.72	1.78	1.83	1.96	2.09	2.21	2.33
		H_s	1,220.2	1,234.1	1,246.2	1,257.4	1,268.2	1,294.0	1,319.3	1,344.3	1,369.2
		n_s	1.5310	1.5462	1.5594	1.5713	1.5824	1.6082	1.6323	1.6550	1.6765

396. To Compute The Quality Of Steam From The Results Of The Throttling Calorimeter, use the following formula which is derived below:

(278) $$\mathbf{x} = \frac{1{,}050 + 0.46T_2 - \mathbf{h}}{\mathbf{L}} \qquad \text{(decimal)}$$

Wherein: $\mathbf{x}$ = the quality of steam, expressed decimally. T_2 = the temperature shown by the thermometer T_2 (Fig. 350) in degrees Fahrenheit. $\mathbf{h}$ = the heat of liquid corresponding to the temperature of the steam, T_1, before passing through the orifice as shown by thermometer T_1 (Fig. 350), in British thermal units per pound. $\mathbf{L}$ = latent heat of steam corresponding to T_1, the same temperature as for $\mathbf{h}$ in British thermal units per pound.

EXAMPLE.—Suppose the temperature of the entering steam, T_1, is 355.8° F. and the temperature of the steam in the exhaust side of the calorimeter, T_2, is 250.3° F. The pressure in the calorimeter chamber, C, is assumed to be practically atmospheric. What is the quality of the steam? SOLUTION.—By For. 278, the quality, $\mathbf{x} = (1{,}050 + 0.46T_2 - \mathbf{h})/\mathbf{L} = (1{,}050 + 0.46 \times 250.3 - 327.4)/865.4 = 0.969$, or 96.9 *per cent.*

DERIVATION.—As the calorimeter is well insulated and there is a sufficient flow of steam so that the heat loss in it may be neglected, the total heat of the steam will be the same before and after passing through the orifice. If the temperature of the wet steam before passing through the orifice is T_1, the corresponding total heat of the wet steam (by For. 242) = $\mathbf{h} + \mathbf{xL}$. If the steam is superheated after passing through the orifice, the total heat of the superheated steam (by For. 244) = $\mathbf{H}_D + \mathbf{C}T_S$. Since the two are equal, $\mathbf{h} + \mathbf{xL} = \mathbf{H}_D + \mathbf{C}T_S$, and:

(279) $$\mathbf{x} = \frac{\mathbf{H}_D + \mathbf{C}T_S - \mathbf{h}}{\mathbf{L}} \qquad \text{(decimal)}$$

Or:

(280) $$\mathbf{x} = \frac{\mathbf{H}_D + \mathbf{C}(T_2 - T_3) - \mathbf{h}}{\mathbf{L}} \qquad \text{(decimal)}$$

Wherein: $T_S = T_2 - T_3$ or the difference between the observed temperature and the temperature corresponding, in a steam table, to the observed pressure after passing through the orifice. When a pressure corresponding to a temperature of about 213° F. is obtained on the atmospheric side of the orifice, the atmospheric values for $\mathbf{H}_D$, $\mathbf{C}$ and T_3 may be substituted and For. (280) becomes:

(281) $$\mathbf{x} = \frac{1{,}150.7 + 0.46(T_2 - 213) - \mathbf{h}}{\mathbf{L}} \qquad \text{(decimal)}$$

And simplifying:

(282) $$\mathbf{x} = \frac{1{,}050 + 0.46T_2 - \mathbf{h}}{\mathbf{L}} \qquad \text{(decimal)}$$

Which is the same as For. (278).

397. When Steam Is Too Wet To Superheat In A Throttling Calorimeter (Sec. 395) its quality may ordinarily be measured in a *separating calorimeter* (Fig. 352). This is a device for mechanically separating and measuring the water suspended in the steam. The quality is found by dividing the weight of dry steam by the sum of the weight of the moisture and the weight of the dry steam. It is impossible, however, to completely separate all of the liquid from the vapor with a separating calorimeter. Hence, such calorimeters always indicate a quality slightly in excess of the actual. When the steam pressure is less than about 50 lb. per sq. in., a separating calorimeter is very inaccurate. A throttling calorimeter may, however, be used on the discharge from the separating calori-

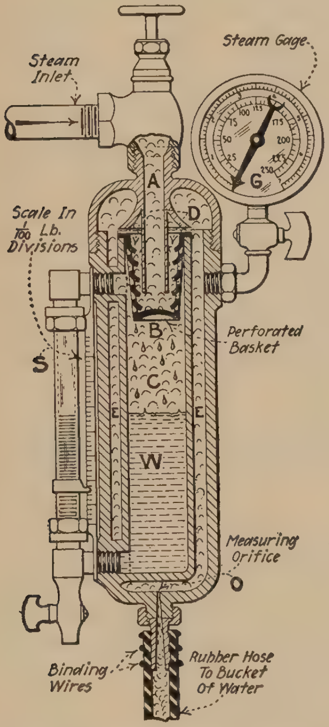


FIG. 352.—Separating calorimeter (which separates, mechanically, the water from the steam).

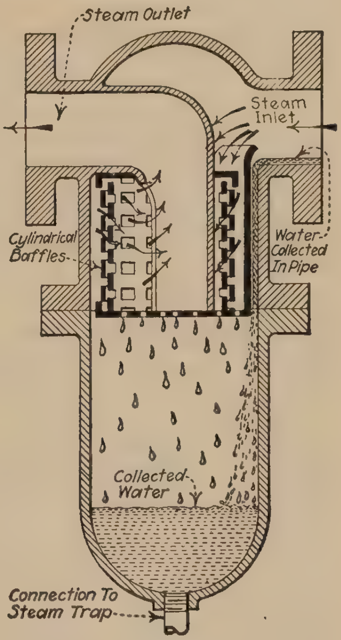


FIG. 353.—Steam separator for removing entrained moisture.

meter so as to correct the error. The operation of the separating calorimeter is explained below.

Explanation.—The steam enters the calorimeter through the tube, *A*, and discharges into the metal basket, *B*, which has perforations through its sides. The bottom of the basket is not perforated. Hence, to reach the outlet, *D*, above, the steam must make a sharp turn as it leaves the tube, *A*. In making this turn, the moisture in the steam, being heavier than the dry vapor, is thrown through the perforations in the side of *B* into the inner chamber, *C*, where it collects. The volume of the water, *W*, thus collected is read on the scale, *S*. The steam passes through, *D*, into the outer chamber, *E*, and then through the orifice, *O*, into the atmosphere or into a bucket of water. The rate of steam flow through the orifice, *O*, will depend on the pressure in *E*. The gage, *G*, has two sets of graduations, one showing the pressure in *E*, and the other showing the weight of steam flow through *O* during a 10-minute period. As this gage for the steam flow is unreliable, a better scheme is to obtain the weight of the steam by condensing it—by passing it into a bucket of water—and then weighing the condensed steam.

Note.—In Steam-engine Practice, Steam Is Usually Passed Through A Separator (Fig. 353) Before It Reaches The Engine. Hence its quality on entering the engine is high enough to be measured in a throttling calorimeter.

398. Ammonia, Carbon Dioxide, And Sulphur Dioxide Vapors Are Used In Refrigeration Practice.—Since in mechanical refrigeration temperatures below 32° F. are required, it is desirable to employ some vapor which has (at moderate pressures) a boiling temperature lower than 32° F. It is difficult to utilize water vapor for refrigeration purposes because water has a relatively high freezing point—it would be a solid at temperatures which must be used in refrigeration. Ammonia, carbon dioxide, and sulphur dioxide are the vapors which are generally employed. Ammonia is a very satisfactory refrigerant for ordinary refrigeration purposes because, at moderate pressures (130–200 lb. per sq. in.), it can readily be condensed with cooling water at temperatures of 50 to 80° F. Sulphur dioxide condenses at pressures of from 40 to 60 lb. per sq. in. even with relatively warm condensing water. Thus this fluid is used to advantage in the tropics. Carbon dioxide is best suited for low-temperature refrigeration, but it must have cool condensing water, for otherwise the efficiency is greatly impaired. Carbon dioxide must be raised to a pressure, of nearly 1,000 lb. per sq. in. before it can be condensed at 80° F.

399. Table Giving The Properties Of One Pound Of Saturated Sulphur-dioxide Vapor from Marks' "Mechanical Engineers' Handbook."

Temp., deg. Fahr.	Pressure, lb. per sq. in. abs.	Heat content—B.t.u. per lb.				Entropy		Specific volume of sat. vapor, cu. ft. per lb.
		Total of vapor	Of liquid	Latent heat		Of liquid	Of vaporization	
				Total	Internal			
(1) T	(2) P	(3) H_D	(4) h	(5) L	(6) L_I	(7) n_L	(8) n	(11) V_D
−15	6.86	160.52	−14.28	174.80	161.04	−0.0308	0.3935	10.910
−10	7.90	161.02	−12.85	173.87	160.00	−0.0274	0.3869	9.510
− 5	9.03	161.50	−11.39	172.89	158.90	−0.0240	0.3803	8.410
0	10.35	161.92	−9.007	171.83	157.70	−0.0208	0.3739	7.490
5	11.80	162.29	−8.388	170.68	156.43	−0.0176	0.3675	6.660
10	13.40	162.59	−6.842	169.43	154.95	−0.0141	0.3608	5.910
15	15.15	162.87	−5.321	168.19	153.59	−0.0110	0.3546	5.210
20	17.09	163.12	−3.780	166.90	152.26	−0.0079	0.3483	4.635
25	19.17	163.30	−2.212	165.51	150.84	−0.0046	0.3418	4.135
30	21.46	163.43	−0.622	164.05	149.36	−0.0012	0.3351	3.716
35	24.04	163.51	+0.968	162.54	147.75	+0.0020	0.3287	3.350
40	26.82	163.55	2.565	160.99	146.11	0.0051	0.3224	3.005
45	29.90	163.53	4.156	159.37	144.40	0.0083	0.3160	2.700
50	33.38	163.45	5.850	157.60	142.68	0.0117	0.3094	2.433
55	36.96	163.33	7.510	155.82	140.92	0.0150	0.3029	2.210
60	40.53	163.19	9.203	153.99	138.95	0.0182	0.2965	2.003
65	44.92	162.99	10.900	152.09	137.12	0.0215	0.2900	1.817
70	49.56	162.73	12.580	150.15	135.29	0.0248	0.2835	1.650
75	54.33	162.44	14.310	148.13	133.28	0.0280	0.2771	1.499
80	59.58	162.09	16.090	146.00	131.16	0.0312	0.2707	1.361
85	65.25	161.70	17.830	143.87	129.04	0.0345	0.2642	1.238
90	71.25	161.25	19.640	141.61	126.85	0.0377	0.2578	1.137
95	77.66	160.74	21.420	139.32	124.63	0.0410	0.2513	1.041
100	84.75	160.19	23.170	137.02	122.39	0.0443	0.2442	0.950

400. Table Giving The Properties Of One Pound Of Saturated Ammonia Vapor (Based on data by Goodenough and Mosher, from Marks'. "Mechanical Engineers' Handbook").

Temp., deg. Fahr.	Pressure, lb. per sq. in. abs.	Heat content—B.t.u. per lb.					Entropy			Specific volume	
		Total of vapor	Of liquid	Latent			Total	Of liquid	Of vaporization	Of liquid, cu. ft. per lb.	Of sat. vapor, cu. ft. per lb.
				Total	Internal	External					
(1) T	(2) P	(3) H_D	(4) h	(5) L	(6) L_I	(7) L_E	(8) n_D	(9) n_L	(10) n_V	(11) V_L	(12) V_D
−40	10.12	526.6	−75.3	601.9	554.2	47.7	1.2690	−0.1653	1.4343	0.0234	25.45
−35	11.74	528.2	−70.2	598.3	550.2	48.1	1.2551	−0.1531	1.4090	0.0235	22.14
−30	13.56	529.8	−65.0	594.7	546.2	48.5	1.2432	−0.1410	1.3842	0.0236	19.35
−25	15.61	531.3	−59.8	591.1	542.1	49.0	1.2308	−0.1290	1.3598	0.0238	16.95
−20	17.91	532.8	−54.6	587.4	538.0	49.4	1.2189	−0.1171	1.3360	0.0239	14.89
−15	20.46	534.3	−49.4	583.6	533.9	49.7	1.2072	−0.1054	1.3126	0.0240	13.15
−10	23.30	535.7	−44.2	579.9	529.8	50.1	1.1958	−0.0938	1.2896	0.0241	11.63
−05	26.46	537.1	−38.9	576.1	525.6	50.5	1.1847	−0.0824	1.2671	0.0242	10.32
0	29.95	538.5	−33.7	572.2	521.4	50.8	1.1740	−0.0709	1.2449	0.0244	9.19
5	33.79	539.9	−28.4	568.3	517.1	51.2	1.1636	−0.0595	1.2231	0.0245	8.20
10	38.02	541.2	−23.2	564.4	512.9	51.5	1.1534	−0.0483	1.2017	0.0246	7.34
15	42.67	542.5	−17.9	560.4	508.6	51.8	1.1434	−0.0372	1.1806	0.0248	6.583

20	47.75	543.7	−12.6	556.3	504.2	52.1	1.1337	−0.0262	1.1599	0.0249	5.920
25	53.30	545.0	−7.3	552.2	499.8	52.4	1.1242	−0.0153	1.1395	0.0250	5.336
30	59.39	546.2	−1.9	548.1	495.4	52.7	1.1150	−0.0044	1.1194	0.0252	4.820
35	65.91	547.4	+3.5	543.9	491.0	52.9	1.1061	+0.0065	1.0996	0.0253	4.364
40	73.03	548.5	8.9	539.7	486.5	53.2	1.0974	0.0173	1.0801	0.0255	3.959
45	80.75	549.7	14.3	535.3	481.9	53.4	1.0889	0.0280	1.0609	0.0256	3.599
50	89.09	550.8	19.8	531.0	477.3	53.7	1.0806	0.0387	1.0419	0.0258	3.278
55	98.03	551.9	25.3	526.5	472.7	53.8	1.0725	0.0494	1.0231	0.0259	2.992
60	107.7	552.9	30.9	522.0	468.0	54.0	1.0647	0.0601	1.0046	0.0261	2.734
65	118.1	554.0	36.5	517.5	463.3	54.2	1.0571	0.0708	0.9863	0.0263	2.503
70	129.2	555.0	42.1	512.8	458.5	54.3	1.0496	0.0813	0.9683	0.0264	2.296
75	141.1	556.0	47.8	508.1	453.7	54.4	1.0423	0.0919	0.9504	0.0266	2.109
80	153.9	557.0	53.6	503.4	448.8	54.6	1.0333	0.1025	0.9328	0.0268	1.940
85	167.4	557.9	59.4	498.5	443.9	54.6	1.0285	0.1132	0.9153	0.0270	1.788
90	181.8	558.9	65.3	493.5	438.9	54.6	1.0218	0.1238	0.8980	0.0271	1.650
95	197.3	559.8	71.3	488.5	433.9	54.6	1.0152	0.1344	0.8808	0.0273	1.524
100	213.8	560.7	77.3	483.4	428.7	54.7	1.0088	0.1450	0.8638	0.0275	1.408
105	231.2	561.6	83.4	478.2	423.5	54.7	1.0026	0.1557	0.8469	0.0277	1.305
110	249.6	562.5	89.6	472.9	418.3	54.6	0.9966	0.1664	0.8302	0.0280	1.210
115	269.2	563.3	95.9	467.4	412.9	54.5	0.9907	0.1722	0.8135	0.0282	1.122
120	289.9	564.2	102.2	461.9	407.5	54.4	0.9850	0.1881	0.7969	0.0284	1.042
125	311.6	565.0	108.7	456.3	402.0	54.3	0.9795	0.1990	0.7805	0.0286	0.970

401. Table Giving The Properties Of One Pound Of Saturated Carbon-dioxide Vapor (from Marks' "MECHANICAL ENGINEERS' HANDBOOK").

Temp., deg. Fahr.	Pressure, lb. per sq. in. abs.	Heat content—B.t.u. per lb.				Entropy		Specific volume	
		Total of vapor	Of liquid	Latent		Of liquid	Of vaporization	Of liquid, cu. ft. per lb.	Of vayor, cu. ft. per lb.
				Total	Internal				
(1) T	(2) P	(3) H_D	(4) h	(5) L	(6) L_I	(7) n_L	(8) n_V	(9) V_L	(10) V_D
−25	203.4	100.22	−26.91	127.13	110.8	−0.0561	0.2925	0.01551	0.4575
−20	221.0	100.50	−24.75	125.25	109.0	−0.0513	0.2851	0.01556	0.4173
−15	240.5	100.74	−22.72	123.46	107.3	−0.0467	0.2778	0.01565	0.3810
−10	261.8	100.88	−20.56	121.44	105.4	−0.0419	0.2702	0.01578	0.3481
− 5	284.1	100.99	−18.31	119.30	103.4	−0.0372	0.2626	0.01594	0.3185
0	308.0	101.00	−16.00	117.00	101.3	−0.0325	0.2549	0.01612	0.2918
5	334.2	100.97	−13.73	114.70	99.2	−0.0276	0.2470	0.01631	0.2672
10	362.5	100.89	−11.36	112.35	96.9	−0.0227	0.2391	0.01652	0.2450
15	391.0	100.70	− 8.94	109.64	94.3	−0.0176	0.2309	0.01675	0.2244
20	421.6	100.43	− 6.40	106.83	91.8	−0.0126	0.2228	0.01696	0.2060
25	454.7	100.08	− 3.74	102.82	88.4	−0.0074	0.2143	0.01720	0.1882
30	488.8	99.43	− 1.04	100.47	86.7	−0.0021	0.2014	0.01747	0.1724
35	525.5	99.00	+ 1.74	97.26	83.6	+0.0032	0.1968	0.01776	0.1580
40	546.5	98.25	4.36	93.89	80.4	0.0087	0.1876	0.01805	0.1444
45	606.0	97.32	7.54	89.78	77.05	0.0145	0.1780	0.01835	0.1323
50	650.0	96.30	10.76	85.54	73.31	0.0205	0.1679	0.01870	0.1205
55	696.0	95.00	14.18	80.82	69.16	0.0268	0.1572	0.01918	0.1090
60	744.0	93.54	17.85	75.69	64.90	0.0334	0.1461	0.01986	0.0986
65	794.0	91.67	21.50	70.17	60.08	0.0406	0.1334	0.02052	0.0890
70	847.0	89.35	26.02	63.33	54.03	0.0483	0.1201	0.02136	0.0816
75	906.0	86.36	30.96	55.40	47.20	0.0576	0.1037	0.02230	0.0706
80	965.0	82.80	36.80	46.00	39.16	0.0684	0.0843	0.02365	0.0614
85	1,026.0	76.60	44.67	30.23	26.80	0.0828	0.0559	0.02620	0.0500
87	1,052.0	71.80	48.98	23.82	18.25	0.0923	0.0393	0.02782	0.0440
88.43	1,071.0	61.45	61.45	0.00	0.00	0.1120	0.000	0.0346	0.0346

QUESTIONS ON DIVISION 11

1. What is the distinction between a vapor and a gas? Do gases and vapors behave similarly?

2. What are the three conditions in which a vapor may exist? Define each in two ways. Which one seldom occurs in practice?

3. What are the two forms of saturated vapor? Define each.

4. How is the amount of superheat in a vapor expressed?

5. How may the condition of a vapor be determined?

6. What is meant by the quality of a vapor?

7. How may the properties of a vapor at some pressure between those given in the table be found?

8. Define heat of the liquid. Total heat of a vapor. Of what values given in the vapor tables is the *total heat* the sum?

9. How may the *total heat* of a wet vapor be found? Of a superheated vapor?

10. Define the *specific volume* of a vapor. How is it determined for wet, dry saturated, and for superheated vapors?

11. How would you find the quality of a wet vapor if you knew only its pressure and specific volume?

12. Give the general formula for finding the internal heat energy in any vaporous substance. What is the starting point from which internal energy is measured?

13. Of what two factors may heat energy be considered the product? Explain the similarity, on this basis, of heat and other forms of energy.

14. Give two definitions of *entropy*. Can a substance suffer an increase or decrease of heat content without suffering a change in entropy? Explain.

15. Can entropy be measured? How are entropy values determined? Do all substances have entropy? Explain.

16. Of what use is entropy in heat calculations? Of what value are charts which employ entropy?

17. Is it possible to determine the absolute entropy of the substance? Why?

18. Do we ever need to know the absolute entropy of a substance? From what starting point is entropy generally measured?

19. What is the difference between absolute entropy and total entropy?

20. How can the change in entropy during heat transfer be determined? Explain fully.

21. Explain the usefulness of the temperature-entropy diagram for any process.

22. What sort of temperature-entropy diagrams are useful in engineering? What is the difference between such a *diagram* and a *chart?*

23. How would you find the entropy of a dry saturated vapor? Of a superheated vapor? Of a wet vapor?

24. What is a *Mollier diagram?* Using values from the steam tables show by a sketch how a Mollier diagram is constructed. Indicate on your sketch what portion of the diagram is generally most used.

25. In how many ways may vapors expand and be compressed? What may be considered as the fundamental expansion or compression processes?

26. What are the three principal kinds of vapor expansions which are encountered in actual machines?

27. What is an *isentropic expansion?* In what kind of machines do nearly isentropic expansions occur? Why is the isentropic expansion considered as the ideal? Explain with a sketch.

28. What changes in quality or superheat accompany isentropic expansions of vapors? How would you determine the quality or superheat of a vapor after isentropic expansion?

29. Where do constant-pressure expansions of vapor occur in practical machines?

30. Under what conditions does a vapor expand without change of heat content? In what practical processes do such expansions occur?

31. What are the three principal ways in which vapors may be compressed? Which of these is not practically attainable? In what machines and under what conditions are these compressions obtained?

32. Derive the energy relations for an isentropic process for a vapor. What quantity can be read directly from a heat-entropy chart?

33. State and derive the energy relations for a constant-pressure process for a vapor.

34. What are the energy relations for throttling and isodynamic processes?

35. What characteristics of steam make it so suitable a medium for heat engines?

36. Make a sketch of and explain the principle of operation of the throttling calorimeter.

37. When cannot a throttling calorimeter be used? What calorimeter is then used and how does it operate? Make a sketch of it. Is this calorimeter very accurate?

38. Under what different conditions of refrigeration are ammonia, sulphur dioxide, and carbon dioxide used? Which of these is most generally used?

PROBLEMS ON DIVISION 11

1. What is the total heat given off in the condensation of 1,500 lb. of wet steam at 20 lb. per sq. in. abs. having a quality of 92.8 per cent. when the condensate is cooled to 60° F.?

2. What amount of heat must be supplied to 1,720 lb. of water at 49° F. to convert it to steam at 185 lb. per sq. in. gage pressure and 432° F.?

3. Steam at 140 lb. per sq. in. abs. and 98 per cent. quality expands in a turbine to a pressure of 2 lb. per sq. in. abs. After this expansion it has a quality of 81 per cent. By calculations from the values given in the Steam Table, find the heat absorbed by the turbine from 1 lb. of steam. Note: Heat absorbed equals heat content of steam at throttle minus the heat content of exhaust steam.

4. Find the specific volume of the steam entering and leaving the turbine of Prob. 3.

5. Find the internal energy of the steam entering and leaving the turbine of Prob. 3.

6. Find, without the use of the chart (Fig. 343), the increase in entropy during the expansion in Prob. 3. How much more heat is in 1 lb. of the exhaust steam than would have been in it, had the steam expanded isentropically?

7. Steam at 160 lb. per sq. in. abs. and 40° F. superheat expands isentropically (that is, along a constant entropy line) to a pressure of 5 lb. per sq. in. abs. By means of the chart find the quality of the steam after this expansion? Find the quality of the steam after expansion by calculation from the entropy values given in the steam tables without using the chart, and check this value with that found by means of the chart.

8. How much external work would be done by each pound of steam during its expansion in a steam-engine cylinder if the steam expanded isentropically from 200 lb. pre sq. in. abs. and 100° F. superheat to a pressure of 3 lb. per sq. in. abs.?

9. In the coils of an ammonia refrigerating system, vapor ammonia of 10 per cent quality and at $-10°$ F. is evaporated at constant pressure until its quality becomes 0.95, How much heat is absorbed by each pound of ammonia and how much external work is done during the process?

10. A throttling steam calorimeter gives readings as follows: Temperature before passing through orifice, 346° F. Temperature after passing through orifice, 256° F Pressure after passing through the orifice, 15 lb. per sq. in. abs. What is the quality of the entering steam?

DIVISION 12

GAS AND VAPOR CYCLES

402. A Cycle May Be Defined As: *A series of processes performed in a definite order or sequence such that, after a definite number of the processes, all concerned substances are returned to their original state and condition.* Figures 354 and 355 show simple cyles; the illustrations are self-explanatory. In heat engineering, cycles generally consist of condition changes of gases or

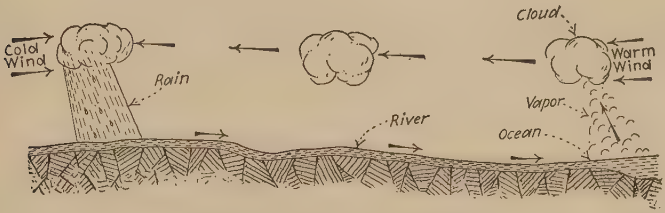


Fig. 354.—A water cycle in nature.

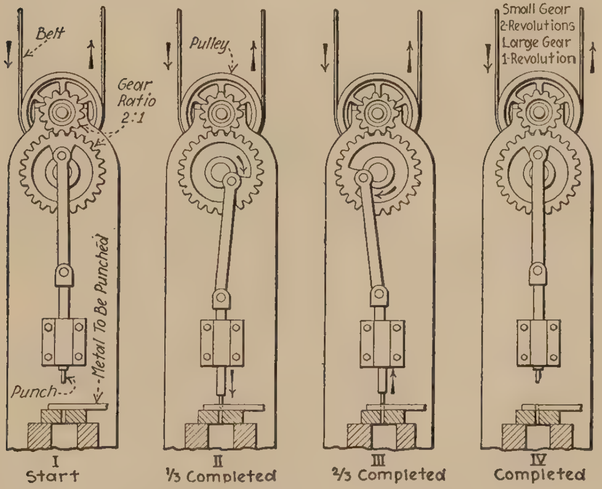
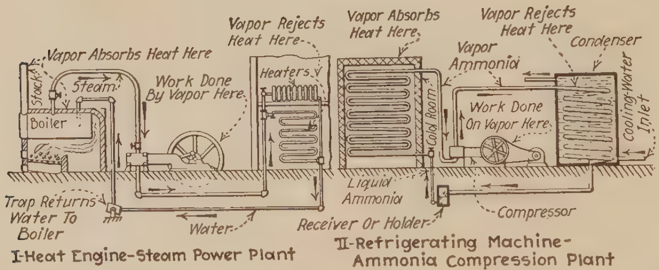


Fig. 355.—A cycle as applied to a machine.

vapors. They may be considered with respect to one machine —as, for instance, the steam engine in a steam power plant or the ammonia compressor in a refrigerating plant—or they may be considered with respect to an entire plant. Each time a pound of water has completed a round trip through the apparatus—boiler, engine, condenser, hotwell, and again back to the boiler—and attained its original condition, it is said to have completed one cycle. When only the processes which occur in a single heat machine (cylinder) are considered and when the weight of the *working substance* (steam, in a steam engine) within the machine is changed from time to time (by admitting and taking away a part of the working substance), then the series of processes does not constitute a *true cycle*. Such a series of processes is sometimes termed a *pseudo cycle* (pseudo meaning false). In this division, both true and pseudo cycles will be discussed.

403. All Heat Engines And Refrigerating Machines Operate on Cycles.—A *heat engine* (Fig. 356-*I*) is any machine which utilizes heat energy for the production of mechanical energy—for example, the steam engine or turbine and the internal combustion engine. A *refrigerating machine* (Fig. 356-*II*) is any machine which utilizes mechanical (or other) energy to accomplish the transfer of heat energy from one body to a relatively hotter body; see also Div. 18. A refrigerating machine may therefore be called a *heat pump*. Generally speaking, if a heat-engine cycle is reversed (the processes,



I-Heat Engine-Steam Power Plant

II-Refrigerating Machine-Ammonia Compression Plant

Fig. 356.—Showing the difference between a heat engine and a refrigerating machine.

Sec. 402, performed in the reverse direction and reverse order), it becomes a *refrigerating-machine cycle* and vice versa—the reversal of the cycle is not possible, however, with all heat-engine cycles. Since heat engines and refrigerating machines operate on cycles, as stated above, the importance of studying cycles becomes apparent. The usefulness of studying cycles is further explained in Secs. 406 to 409. In this division, the more important heat-engine and refrigerating-machine cycles will be discussed.

Note.—The Three Essential Elements Of Every Heat Engine And Refrigerating Machine are: (1) *A hot body* which serves as a source of heat for a heat engine or as a receiver of heat for a refrigerating machine. (2) *A working substance.* (3) *A cold body* which serves as a receiver of heat for a heat engine or as a source of heat for a refrigerating machine. *During the operation of a heat engine,* heat energy leaves the hot body passing to the working substance by means of which substance a portion of the heat energy is transformed into mechanical work; the remainder of the heat energy is rejected from the working substance to the cold body so that the working substance may return to its initial condition and be ready to start a new cycle. This operation is explained in following Sec. 410. *During the operation of a refrigerating machine* (Fig. 356) heat energy leaves the cold body passing to the working substance which, by means of mechanical work done on it, is made capable of rejecting the heat energy to the hot body. This operation is explained in following Sec. 433. *The working substance* may be a solid, liquid, vapor, or gas—although, in engineering, vapors and gases are most commonly used. A heat engine utilizing a solid body as a working substance is shown in Fig. 150.

404. The "Thermal Efficiency" Of A Heat Engine is defined as the ratio of the heat converted into work (output) to the heat supplied to it from the hot body (input). This definition is quite general. Inasmuch as the work output of the engine (at the shaft) is always less than the total work resulting from the conversion of heat, the thermal efficiency may be considered on the basis of either of these two quantities. It should, therefore, always be clearly understood and stated on which basis the thermal efficiency is considered (see also Sec. 436). In the following sections, the thermal efficiency will be considered on the basis of work which actually (or theoretically) results from the conversion of heat energy. The definition for the term as herein used, may be expressed by the formula:

$$(283)\quad \textit{Thermal efficiency} = \frac{\textit{Heat converted into work}}{\textit{Heat supplied from hot body}} \quad \text{(decimal)}$$

It is obvious from the definition that engines with high thermal efficiencies are more desirable than are engines with low efficiencies.

EXAMPLE.—A gas engine (Fig. 357) consumes 20 cu. ft. of a gas (each cubic foot representing 500 B.t.u.) in developing 1 hp.-hr. What is its thermal efficiency? SOLUTION.—The *heat supplied* = 20 × 500 = 10,000 *B.t.u.* Since 1 hp.-hr. = 2,545 B.t.u., by For. (283), the *thermal efficiency* = (*Heat converted into work*)/(*Heat supplied from hot body*) = 2,545 ÷ 10,000 = 0.254,5 or 25.45 *per cent.*

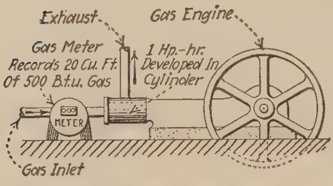

Exhaust
Gas Engine
Gas Meter Records 20 Cu. Ft. Of 500 B.t.u. Gas
1 Hp.-hr. Developed In Cylinder
METER
Gas Inlet

FIG. 357.—What is the thermal efficiency?

405. The "Coefficient Of Performance" Of A Refrigerating Machine is defined as the ratio of the heat abstracted from the cold body (output) to the heat equivalent of the energy required (input). As with thermal efficiencies, the coefficient of performance may be considered on the basis of the work actually done on the working substance or on the basis of the work input to the machine at its shaft. On which basis the coefficient of performance is being considered should always be clearly stated and understood. In the following sections, the coefficient of performance will be considered on the basis of the work actually done on the working substance. The definition for the term as herein used may be expressed by the formula:

$$(284)\quad \textit{Coefficient of performance} = \frac{\textit{Heat abstracted from cold body}}{\textit{Heat equivalent of energy supplied}} \quad \text{(number)}$$

It is self-evident that a high coefficient of performance is desirable.

EXAMPLE.—A test of an ammonia refrigerating plant (Fig. 358) shows that 5 hp. is expended in compressing the ammonia while 50,000 B.t.u. per hr. is extracted from the cold room. What is the coefficient of performance? Solution.—Since (Sec. 82) 1 hp. = 2,545 B.t.u. per hr., 5 hp. = 5 × 2,545 = 12,725 *B.t.u. per hr.* Hence, by For. (284), the *coefficient of performance* = (*Heat abstracted from cold body*)/(*Heat equivalent of energy supplied*) = 50,000 ÷ 12,725 = 3.92.

406. The Various Cycles Provide Ideal Ultimate Goals For Judging Or Comparing the actual performances of the heat engines and plants of the various types. These cycles—which, remember, are ideally perfect—are useful concepts in somewhat the same way as are the ideas of "a perfect gas" and "a frictionless surface." Thus, as will be shown, the *cycle efficiency* of an engine or plant can be calculated (on the basis of the actual temperatures which obtain in the plant) on the *assumption* that the engine or plant is operating in conformity with one of these ideal cycles. This efficiency will then show what proportion of the heat input to the engine or plant would be realized as work output if the plant were actually operating in accordance with the processes of the assumed ideal cycle and through the temperature ranges which actually obtain for the engine or plant.

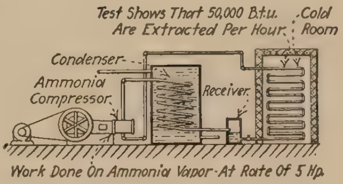

Test Shows That 50,000 B.t.u. Are Extracted Per Hour.
Cold Room
Condenser
Ammonia Compressor.
Receiver.
Work Done On Ammonia Vapor At Rate Of 5 Hp.

Fig. 358.—What is the coefficient of performance?

407. The Usefulness Of Studying Cycles, as is hereinafter done, lies in the facts that: (1) The study of any cyclic series of processes reveals (from a consideration of the proposed thermal conditions—temperatures and pressures), without actually building a heat machine—or plant—to utilize the processes, an upper limit or maximum which the thermal efficiency or coefficient of performance cannot possibly exceed. (2) The study of cycles reveals in advance the effect (upon the efficiency or coefficient of performance) that will follow from changes in the condition of the working substance at different phases of the cycle—for example: the effect of changing the temperatures between which a machine operates, may be foretold. (3) The study guides designers and inventors by revealing how much and in what manner the actual efficiency or performance of a given heat machine or plant falls short of that of a theoretically perfect machine which operates on the same cycle. (4) Cyclic study also enables comparisons to be made between different heat machines or plants which operate on the same cycle but with different temperatures—comparisons of the degree of perfection of the actual machines or plants.

Explanation.—Thermal Efficiencies And Coefficients Of Performance Have Upper Limits Or Maximums, Depending On The Nature Of The Processes Which Constitute The Cycle, and on the temperature and condition of the working substance at different phases of the cycle. Heat machines differ in this way from mechanical and electrical machines. Mechanical and electrical machine can theoretically be constructed so as to have as high an efficiency as desired—100 per cent. being the limit. Practically, the efficiencies of such machines cannot be made quite 100 per cent., but they can, by proper design and construction be made reasonably near this limit. Electric motors for example, have been made with efficiencies as high as 98 per cent. Heat machines, however, have always an upper limit of efficiency—much less than 100 per cent. for heat engines—which they cannot possibly exceed. The reason for this limit is that it is not feasible to reject heat at any temperature below that of the coldest nearby natural object. The value of this upper limit is determined by the cycle upon which the heat machine operates and by the thermal conditions—temperatures and conditions of the working substance at different phases of the cycle.

Explanation.—The Effect Of Changing Conditions Of The Working Substance During A Cycle May Be Foretold By Cyclic Study by calculating the upper limit of thermal efficiency or coefficient of performance for the new and the old conditions. Thus, the effect of increasing the boiler pressure upon the efficiency of a steam power plant (Fig. 361) may be foretold with reasonable accuracy by computing the upper limit of the thermal efficiency of its cycle under both the old and new conditions. Thus cyclic study indicates to power-plant designers what plant conditions will be most economical.

Explanation.—Cyclic Study Reveals Discrepancies Between Actual And Theoretical Efficiencies And Performances.—By comparison, it may be ascertained why a given heat engine or refrigerating machine or plant fails to fulfill the theoretical expectations. Such comparisons may then be used as a guide by designers and inventors in directing their effects. Such comparisons have probably been the stimulus in producing the compound and uniflow steam engines and the successful steam turbine.

Explanation.—Cycles Make Possible Comparisons As To Degree Of Perfection Between Different Heat Machines which utilize the same processes but with different conditions. Thus, when a designer builds a machine to operate under different conditions than all of his former machines, he may (by computing the cylinder efficiency, Sec. 436) ascertain whether the new machine exhibits the same degree of perfection as the former machines—if it does not, he may have to redesign the new machine.

408. The Reason For The Existence Of The Various Cycles such as the Carnot, the Rankine, the Otto and the Diesel cycles (all of which are discussed hereinafter) is this: Each (except the Carnot) provides a sequence of ideal hypothetical processes which are to a greater or less degree approximated and approached—but which, because of unavoidable losses, can never be realized—in the actual performance of a heat engine (or power plant) of some certain type. As will be shown the Carnot cycle comprehends the sequence of processes that will give the maximum efficiency possible for *any* heat engine. The Rankine cycle employs a sequence which provides a standard for steam power plants. The Otto and the Diesel cycles provide standards for internal-combustion-engine plants.

Examples.—In the example under Sec. 419, cycle efficiencies of a steam power plant are considered. In this plant, the boilers deliver steam of 95 per cent. quality to the prime mover at a pressure of 125 lb. per sq. in. abs. (344.4° F.). The prime mover exhausts into a condenser in which the pressure is 2 lb. per sq. in. abs. (126.15° F.). For this plant (as there shown) the Carnot-cycle efficiency is 27.2 per cent.; the Rankine cycle efficiency is 24.6 per cent. This means that no theoretically-perfect heat engine (or plant), regardless of how effectively it was operated or how perfectly it was constructed, which received its heat at 344.4° F. and rejected its heat at 126.15° F., could possibly have an efficiency greater than 27.2 per cent.—which is the *Carnot-cycle efficiency* for these thermal conditions. That is, with the temperature range stated, it would be impossible *with any sequence of processes or with any heat engine*, regardless how perfect, to convert more than 27.2 per cent. of the received heat into work. Similarly, the Rankine-cycle efficiency of 24.6 per cent. means that no ordinary steam power plant operating under the steam conditions specified could have an efficiency greater than 24.6 per cent.

409. Cycles Are Most Easily Studied By Diagrams which are called *cycle diagrams* (Figs. 360 and 362) and which serve as pictures to relieve the student of the necessity of holding in his mind so many different quantities as are generally involved in cyclic problems. For the study of cycles, as will be shown, the *pressure-volume diagram* and the *tem-*

perature-entropy diagram are most convenient. With these diagrams it is possible to picture the changes in pressure, volume, and temperature of the working substance, and often to represent by areas the work done and the heat added either during any process or during the entire cycle.

Note.—Cycles Are Always Represented On The Pressure-volume And On The Temperature-entropy Planes By Closed Diagrams, as will be evident from a consideration of the examples which follow.

410. The Simplest Cycle, Probably, Is That Of The Non-expansive Engine of which the steam end of a direct-acting steam pump, Fig. 359, is a common example. So far as the machine itself is concerned, the cycle is briefly this: The valve *V*, being in the position shown, steam is admitted from the inlet pipe, *I*, to the left end of the cylinder, *C*, where it exerts its pressure on the piston, *P*, and forces *P* to the right. After *P* has been forced to the right the required amount, the valve, *V*, is automatically moved rapidly to the left. This admits steam to the right side of the piston and also opens a passage for the steam to flow from the left end of *C* to the atmosphere (through *A*). The steam then forces *P* to the left. When *P* has moved to the left the required amount, *V* is again thereby automatically shifted to the right (to the position shown in Fig. 359). The cycle has thus been completed. Inasmuch as the weight of steam in the cylinder *C* is different at different times during a cycle, the processes constitute a *pseudo cycle* (Sec. 402). How the cycle may be considered as a true cycle and how it may be pictured are explained below.

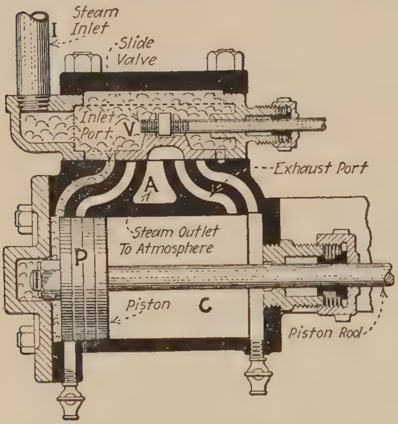


Fig. 359.—Section through cylinder and valve of a direct-acting steam pump.

EXPLANATION.—REPRESENTATION OF THE NON-EXPANSIVE-ENGINE CYCLE BY A PRESSURE-VOLUME DIAGRAM.—Assume that, in the position shown in Fig. 359, the volume of the cylinder to the left of the piston is 0.075 cu. ft. and that the steam is supplied at 100 lb. per sq. in. gage (boiler pressure) or 114.7 lb. per sq. in. abs. This pressure and volume may be plotted on squared paper as indicated at *A*, Fig. 360. The pressure of the steam will force the piston toward the right. After the piston has moved a certain distance to the right, the valve, *V*, is automatically shifted toward the left. Assume that, at the instant *V* is shifted to the left, the volume at the left of the cylinder is 0.725 cu. ft. Now, as the piston is forced to the right by the steam, the steam pressure remains constant. At the instant of shifting, therefore, the pressure and volume are as represented by *B*, Fig. 360. Also, the process during which the piston was forced toward the right is represented by the straight line *AB*. As shown in Sec. 262, the area *FABE* represents the work done during this constant-pressure process.

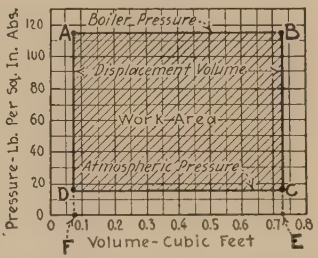


FIG. 360.—Pressure-volume diagram for a non-expansive engine cycle.

Now as the valve, *V*, is quickly and automatically shifted to the left, the steam is released from the left side of the cylinder and flows into the atmosphere. The pressure on the left side of the piston therefore decreases from 100 lb. per sq. in. gage to 0 lb. per sq. in. gage (14.7 lb. per sq. in.) in a very short interval of time during which the piston has (practically) not moved. The left end of the cylinder therefore holds 0.725 cu. ft. of steam at 0 lb. per sq. in. gage as represented by the point *C*, Fig. 360. Line *BC* represents the process of releasing the steam pressure in the cylinder. Since the area under line *BC* is zero, the diagram shows that no work has been done during this releasing process.

As the piston is now moved to the left, it forces out the steam at its left. If it forces out all but 0.075 cu. ft., then line *CD*, Fig. 360, will represent the exhaust process and the area *ECDF* will represent the work done in expelling the steam. The instantaneous (practically) rise in pressure to 100 lb. per sq. in. gage when the valve, *V*, is again automatically shifted to the right is represented by the line *DA*. Since the area under *DA* is zero, no external work is done in raising the pressure.

Thus, the entire cycle for one end of the cylinder is pictured on the pressure-volume plane by the closed diagram *ABCDA* in Fig. 360. The cycle for a non-expansive engine of given dimensions and working between given pressures would be represented by the same pressure-volume diagram regardless of whether the working substance were steam, air, or any other gas or vapor. The temperature-entropy diagram would, however, be different for different working substances and for the same substances working between different temperatures.

Explanation.—Determination Of The Temperatures In The Non-expansive-engine Plant Cycle.—Before constructing the temperature-entropy diagram (Fig. 362) it is necessary to know the exact condition of the working fluid at one point (at least) in the cycle. Furthermore, as suggested in Sec. 402, the cycle must be considered with respect to the entire plant in which the given machine forms but one part. Now, for the non-expansive steam engine (Fig. 359) which was explained above, assume that the plant consists of the equipment shown in Fig. 361. Assume further that the water in the tank, H, is at the temperature of 212° F.—it will be shown later why 212° F. is used. The water is pumped by a small pump, F, from H into a boiler, B. In B the water is heated and evaporated; it leaves B as dry saturated steam at 100 lb. per sq. in. gage.

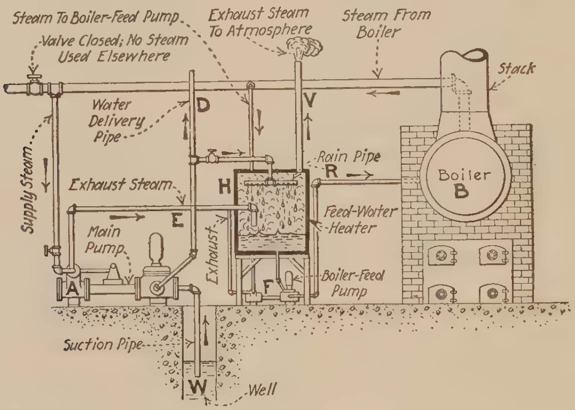


Fig. 361.—An elementary steam power plant (a pumping plant) using steam non-expansively.

The steam then passes to the pump, A, which is the non-expansive engine (Fig. 359) under consideration. Pump A does mechanical work by drawing water from the well W and forcing it out, against a pressure, through D. After being used by A, the steam is rejected through pipe E into tank H. A portion of the water delivered by A is admitted into a perforated pipe, R, in H. In falling through the steam in H, the water from R condenses a portion of the steam therein and is thereby heated to the temperature of the steam. Since the tank is open to the atmosphere, the steam will be at 212° F. Since all of the steam is not condensed by the water from R, the remainder will pass out through the vent pipe, V, into the atmosphere. To make the cycle complete, assume that this steam is formed into clouds which are then precipitated as rain (Fig. 354)—the rain water being returned to W.

NOTE.—TO CORRELATE FIGS. 360 AND 361, assume that sufficient water is pumped from H to B (Fig. 361) to just produce 0.725 cu. ft. of dry saturated steam at 100 lb. per sq. in. The feed pump, F (Fig. 361) raises the pressure of this water from practically atmospheric pressure to 100 lb. per sq. in. gage. This corresponds to process DA Fig. 360. As this water is evaporated in B (Fig. 361) it passes to A and completely fills the cylinder end and pushes out the piston; this is process AB (Fig. 360). Then, as the valve in A is shifted, this steam is released and its pressure immediately decreases to atmospheric. This is process BC (Fig. 360). Finally, as this steam is exhausted from A (Fig. 361), it is all transferred to H, part by way of the atmosphere, clouds, and rain, the other part by condensation in H. This is process CD (Fig. 360).

EXPLANATION.—TO CONSTRUCT THE TEMPERATURE-ENTROPY DIAGRAM FOR THE NON-EXPANSIVE ENGINE PLANT OF FIG. 361, lay off scales OY and OX (Fig. 362) on cross-section paper. *Temperature-entropy diagrams are generally constructed for* 1 *lb. of the working substance.* Hence, the point D of the cycle (Fig. 360), since it represents water at 212° F. may be plotted on Fig. 362 at D (the entropy value is taken from the steam table) temperature and entropy of the water are unchanged by the feed pump (F, Fig. 361), the point D (Fig. 362) also corresponds to point A (Fig. 360). In the boiler, the heat which is first added to the water raises its temperature to the boiling point and then evaporates it at constant temperature. The *heat added* to the water in the boiler is represented by the area $D'DABB'$ in Fig. 362. The process BC of Fig. 360, although it appears to be a constant-volume change, is actually very nearly a constant-heat expansion—the steam, being released from the cylinder, expands without doing external work. Hence the release of the steam may be represented in Fig. 362 by the line BC. The area $B'BCC'$ represents heat added to the steam during this expansion *by friction of the steam.* As the steam is then condensed at atmospheric pressure, *heat* is *abstracted* from it as represented by the area $C'CEDD'$.

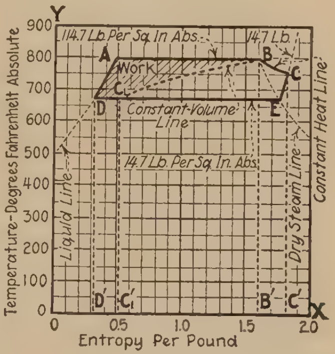


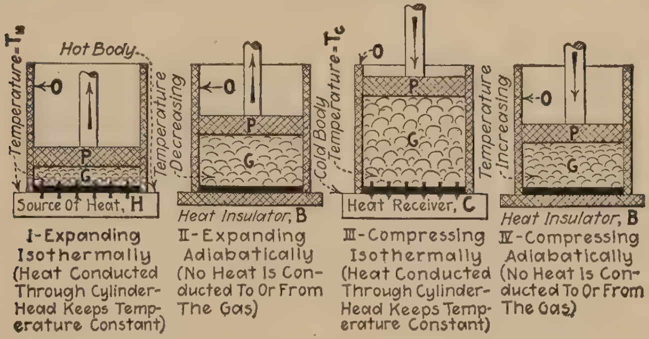
FIG. 362.—Temperature-entropy diagram for a non-expansive steam engine cycle.

Now, it will be convenient to construct a slightly different temperature-entropy diagram from $DABCED$ which would also conform to the pressure-volume diagram $DABCD$ of Fig. 360 but which would represent a cycle during which no heat is added to the steam by its own friction. To do this, assume that, instead of releasing the steam from the cylinder at B (Fig. 360), heat is abstracted from the steam so as to decrease its pressure to 14.7 lb. per sq. in. abs. without changing its volume. This process would also be represented by line BC in Fig. 360 but this would be a frictionless process. This process would be represented in Fig. 362 by BC_1 and the abstracted heat would be represented by the area $B'BC_1C_1'$. To condense the remaining steam at C, Fig. 360, a quantity of heat as represented by $C_1'C_1DD'$ must yet be abstracted. Hence, the total *heat abstracted* is represented by the area $B'BC_1DD'$. Now, since no friction occurs in this cycle, the difference between the heat added and the heat abstracted must give the external work done. Hence, (*area* $D'DABB'$) − (area $D'DC_1BB'$) = *external work* = $DABC_1D$ (shaded in Fig. 362). Since the temperature-entropy diagram is constructed for 1 lb. of steam, the shaded area represents the external work done by 1 lb. of steam in the engine of Fig. 359.

411. A Convenient Method Of Comparing Engines Of Different Kinds Is To Calculate The Efficiency They Would Have If They Were Working On A Perfect Cycle (Shealy) in which case they would convert into work the largest possible proportion of the heat supplied to them. In this *perfect cycle*, all of the heat taken into the engine is at the maximum temperature and all of the heat is rejected from the engine at the minimum temperature. Hence, all of the heat which is utilized by the engine is changed into work by falling through the greatest possible range of temperature. This enables the engine to perform the greatest possible amount of work. Such a cycle is called Carnot's cycle.

412. The Carnot Cycle Is A Theoretical Heat-engine Cycle which was devised by a French scientist named Carnot, principally to show, as will be shown here (Sec. 416), that the efficiency of *any* heat engine cannot exceed a certain value, which depends on the maximum and minimum temperatures of the working substance during the cycle. That is, as is explained in Sec. 416 the efficiency of the Carnot engine cannot be exceeded by any other engine operating with the same hot and cold bodies. No attempt has ever been made to build a heat engine to operate on the Carnot cycle. If such an engine were built, its size would be so great with respect to its power output that its mechanical losses would far offset the gain over other engines due to its higher efficiency. The Carnot cycle is explained below.

Explanation.—The Carnot engine (Fig. 363) presupposes for its operation: (1) A hot body as a source of heat, H, whose temperature remains constant (T_H) no matter how much heat is abstracted from it. (2) A cold body as a receiver of heat, *C*, whose temperature remains constant (T_C) no matter how much heat is added to it. (3) A cylinder, *O*, with sides which are perfect non-conductors of heat and with an end which is a perfect conductor of heat. (4) A piston, *P*, of perfectly non-heat-conducting material. (5) A block, *B*, of perfect heat-insulating material. The working substance, *G*, which may be either a vapor or a gas, is enclosed in the cylinder between the piston and the conducting end of the cylinder. The cylinder must be so arranged that *H*, *C*, and *B* can at will be placed against its end.



I-Expanding Isothermally (Heat Conducted Through Cylinder-Head Keeps Temperature Constant)
II-Expanding Adiabatically (No Heat Is Conducted To Or From The Gas)
III-Compressing Isothermally (Heat Conducted Through Cylinder-Head Keeps Temperature Constant)
IV-Compressing Adiabatically (No Heat Is Conducted To Or From The Gas)

FIG. 363.—Carnot's engine.

Assume for the present that the working substance is a gas and that it is confined in a small volume and at the temperature (T_H) of the heat source, *H*, as shown in Fig. 363-*I*. Let the gas expand slowly. Its temperature will tend to decrease but, since the cylinder end is a perfect heat conductor, heat will flow from *H* to *G* and maintain the temperature of *G* constantly at T_H. After an interval (*II*, Fig. 363), let *H* be removed from the cylinder end and let *B* be immediately put there. Let the expansion of *G* proceed. The expansion will be adiabatic because no heat can now flow to or from the gas. When the temperature of the gas has been lowered to that of the heat receiver, let the expansion be stopped and let *B* be replaced by *C* (Fig 363-*III*). Let the gas be now compressed. Its temperature will tend to rise but, since the cylinder end is a perfect heat conductor, heat will flow from *G* to *C* and maintain the temperature of G constantly at T_C. Let the isothermal compression be stopped at such a point (*IV*, Fig. 363) that, *C* being replaced by B, adiabatic compression to the initial volume (as in *I*) will increase the temperature of *G* to T_H and thus restore the gas to its initial condition. The pressure-volume diagram of the cycle will appear as shown in Fig. 364. The temperature-entropy diagram will appear as shown in Fig. 365.

NOTE.—IT FOLLOWS FROM THE ABOVE DESCRIPTION OF THE CARNOT CYCLE THAT CERTAIN RELATIONS MUST EXIST BETWEEN THE PRESsures And Volumes of the gas at the different points A, B, D, and E (Fig. 364). As stated above, the isothermal compression III must cease at just the right point. By applying For. (239) to the adiabatic process II, there results:

$$V_D = V_B \left(\frac{T_B}{T_D}\right)^{\frac{1}{k-1}} \qquad \text{(volume)} \tag{285}$$

where $\mathbf{k}$ is the adiabatic exponent (C_P/C_V). But, since $T_B = T_H$ and $T_D = T_C$, For. (285) may be written:

$$V_D = V_B \left(\frac{T_H}{T_C}\right)^{\frac{1}{k-1}} \qquad \text{(volume)} \tag{286}$$

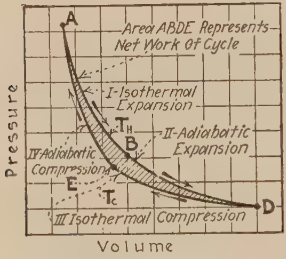


Fig. 364.—Pressure-volume diagram (general) for the Carnot heat-engine cycle with a gas as the working substance.

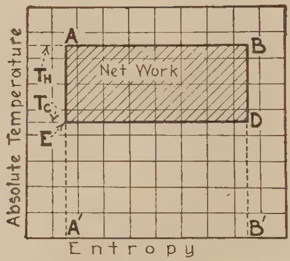


Fig. 365.—Temperature-entropy for the Carnot cycle.

Likewise, by applying For. (239) to the adiabatic process IV, there results:

$$V_A = V_E \left(\frac{T_E}{T_A}\right)^{\frac{1}{k-1}} \qquad \text{(volume)} \tag{287}$$

But, since $T_E = T_C$ and $T_A = T_H$, For. (287) may also be written:

$$V_A = V_E \left(\frac{T_C}{T_H}\right)^{\frac{1}{k-1}} \qquad \text{(volume)} \tag{288}$$

Or, by transposing

$$V_E = V_A \left(\frac{T_H}{T_C}\right)^{\frac{1}{k-1}} \qquad \text{(volume)} \tag{289}$$

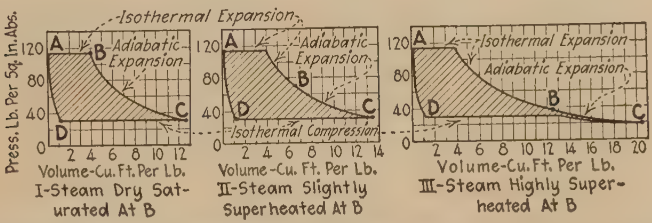
Now, from Fors. (286) and (289), there can be written the proportion:

$$V_D : V_B :: V_E : V_A \qquad \text{(proportion)} \tag{290}$$

In a similar manner it can be shown that:

$$P_A : P_B :: P_E : P_D \qquad \text{(proportion)} \tag{291}$$

413. When A Vapor Is Used As The Working Substance In A Carnot Engine, the pressure-volume diagram generally will be different from Fig. 364 (only if the vapor remained superheated during all of the process would the pressure-volume diagram have the appearance of Fig. 364). The quality of the vapor (if it is not always superheated) will be the least either at the beginning or end of the adiabatic compression (*IV*, Fig. 363). If, during this compression, the vapor is very wet, the quality will be least at its end; if the vapor is quite dry, the quality will be least at the beginning. Assume that the quality at the end of the compression is zero; then the pressure-volume diagram will appear as *I*, *II*, or *III* of Fig. 366, depending on whether the vapor is saturated, slightly superheated, or highly superheated at the end of the isothermal expansion *AB*.



Volume-Cu. Ft. Per Lb. I-Steam Dry Saturated At B

Volume-Cu. Ft. Per Lb. II-Steam Slightly Superheated At B

Volume-Cu. Ft. Per Lb. III-Steam Highly Superheated At B

Fig. 366.—Pressure-volume graphs for the Carnot cycle with 1 lb. of steam as the working substance and operating between the temperatures of 339 and 250° F. (Steam entirely condensed at *A*.)

Note.—The Temperature-entropy Diagram For All Carnot Engines, even those in which the working substance is a vapor, has the general form shown in Fig. 365.

414. The Thermal Efficiency Of The Carnot Cycle (see Sec. 404 for definition of thermal efficiency) may be readily computed by the following formula, the derivation of which is shown below:

$$\mathbf{E} = \frac{\mathbf{T}_H - \mathbf{T}_C}{\mathbf{T}_H} \qquad \text{(decimal)} \tag{292}$$

Wherein: $\mathbf{E}$ = the thermal efficiency of the Carnot cycle, expressed decimally. $\mathbf{T}_H$ = the absolute temperature of the hot body or source of heat, on any scale. $\mathbf{T}_C$ = the absolute temperature of the cold body or receiver of heat, on the same scale as $\mathbf{T}_H$ is measured.

Derivation.—Since Fig. 365 represents the Carnot cycle for any working substance, the area $A'ABB'$ represents the heat taken from the source during one cycle for a given weight of working substance. Likewise, the area $B'DEA'$ represents the corresponding amount of heat rejected to the receiver. The difference between these two areas, that is the area $ABDE$, therefore represents the amount of heat taken from the source and *not* rejected to the receiver. This obviously is the heat which is converted into work. Therefore, from the definition of thermal efficiency (Sec. 404),

$$\text{(293)} \qquad \mathbf{E} = \frac{area\ ABDE}{area\ A'ABB'} \qquad \text{(decimal)}$$

But, from Fig. 365,

$$\text{(294)} \qquad area\ A'ABB' = (distance\ A'B') \times \mathrm{T}_H \qquad \text{(area)}$$

and

$$\text{(295)} \qquad area\ ABDE = (distance\ A'B') \times (\mathrm{T}_H - \mathrm{T}_C) \qquad \text{(area)}$$

Therefore, by dividing (295) by (294)

$$\text{(296)} \ \frac{area\ ABDE}{area\ A'ABB'} = \frac{(\mathrm{T}_H - \mathrm{T}_C) \times (distance\ A'B')}{\mathrm{T}_H \times (distance\ A'B')} = \frac{\mathrm{T}_H - \mathrm{T}_C}{\mathrm{T}_H} \ \text{(decimal)}$$

and, substituting from (296) into (293), there results

$$\text{(297)} \qquad \mathbf{E} = \frac{\mathrm{T}_H - \mathrm{T}_C}{\mathrm{T}_H} \qquad \text{(decimal)}$$

which is the same as For. (292)

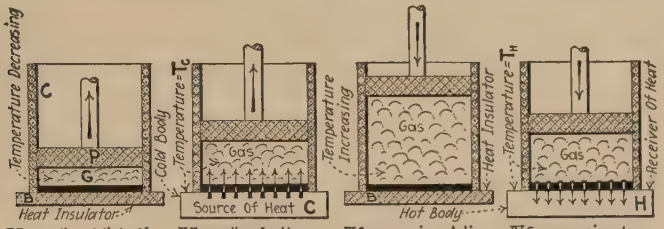
Example.—(See also example under Sec. 419). What is the thermal efficiency of the Carnot cycle if the temperature of the source and receiver are respectively 1,000 and 80° F.? Solution.—By For. (292), the thermal efficiency $= \mathbf{E} = (\mathrm{T}_H - \mathrm{T}_C)/\mathrm{T}_H = (1{,}000 - 80) \div (80 + 460) =$ 0.17 or 17 *per cent.*

Note.—In Finding The Value Of The Term "$\mathrm{T}_H - \mathrm{T}_C$," It Is Unnecessary To Change Each Temperature To Its Value On The Absolute Temperature Scale. The difference between two Fahrenheit temperatures is the same as the difference between the same temperatures expressed in degrees Fahrenheit absolute.

415. The Carnot Engine Becomes A Refrigerating Machine when the engine is supplied with mechanical energy and operated in the reverse direction from that explained in Sec. 412 (see explanation below). In Sec. 403 it was suggested that, theoretically with some exceptions, heat engines when reversed become refrigerating machines. The "reversed" Carnot cycle is as follows:

Explanation.—Assume that the Carnot engine which was described in Sec. 412, is now operated as shown in Fig. 367, the temperature, pressure, and volume of the gas in *I*, Fig. 367, being the same as in *I*,

Fig. 363. The processes illustrated in Fig. 367 may be represented by the pressure-volume diagram of Fig. 368. The temperature-entropy diagram will again appear as shown in Fig. 365 except that now the area *ABDE* represents work done *on* the gas instead of *by* the gas. The heat abstracted from the cold body (the output of a refrigerating machine, Sec. 405) is represented in Fig. 365 by the area *A'EDB'*. Hence, the *coefficient of performance = (area A'EDB') ÷ (area ABDE)*. Expressed in terms of the temperatures.



I-Expanding Adiabatically (No Heat Conducted To Or From Gas)

II-Expanding Isothermally (Heat Conducted Through Cylinder-Head Keeps Temperature Constant)

III-Compressing Adiabatically (No Heat Conducted To Or From Gas)

IV-Compressing Isothermally (Heat Conducted Through Cylinder-Head Keeps Temperature Constant)

FIG. 367.—Refrigerating machine operating on reversed Carnot cycle.

$$\text{(298)} \qquad \textit{Coefficient of performance} = \frac{T_C}{T_H - T_C} \qquad \text{(number)}$$

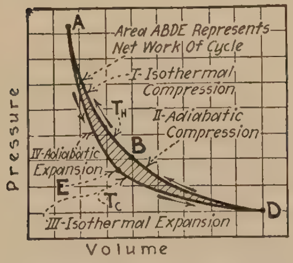


FIG. 368.—Pressure-volume diagram for the Carnot refrigerating machine with a gas as the working substance. (Compare with Fig. 364.)

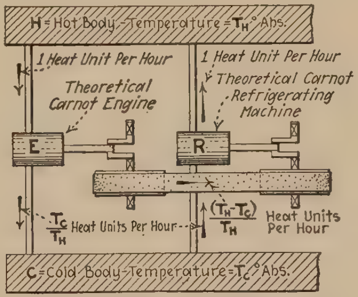

H = Hot Body - Temperature = T_H° Abs.
1 Heat Unit Per Hour
Theoretical Carnot Engine
1 Heat Unit Per Hour
Theoretical Carnot Refrigerating Machine
E
R
T_C/T_H Heat Units Per Hour
(T_H - T_C)/T_H Heat Units Per Hour
C = Cold Body - Temperature = T_C° Abs.

FIG. 369.—Imaginary arrangement of a Carnot engine driving a Carnot refrigerating machine.

416. The Efficiency Of The Carnot Engine Cannot Be Exceeded By Any Other Engine Operating With The Same Hot And Cold Bodies.—This is a very important relationship inasmuch as it affords a criterion of the maximum efficiency that can be attained by any heat engine. The proof of the statement follows.

PROOF.—First imagine an arrangement, as suggested in Fig. 369, of a Carnot engine, E, driving a Carnot refrigerating machine, R, both machines utilizing the same hot and cold bodies H and C. From For. (283), by transposition, there results: *Heat converted into work* = (*Heat supplied from hot body*) × (*Efficiency*). And, from For. (292), the efficiency of a Carnot engine = $(T_H - T_C)/T_H$. For each unit of heat that is supplied from H to E, there will be converted into work: $1 \times [T_H - T_C/T_H] = T_H - T_C/T_H$ heat units. The difference between the heat supplied to E and the heat which E converts into work will be rejected to C. Hence, heat rejected to C for each heat unit supplied to $E = 1 - (T_H - T_C/T_H) = T_C/T_H$ heat units.

Now, assume that the work developed in E is all expended in driving R. Then, for each heat unit supplied to E, $T_H - T_C/T_H$ heat units will be supplied, as work, to R. From For. (284), by transposition, there results: *Heat abstracted from cold body* = (*Coefficient of performance*) × (*Work supplied*). And, from For. (298), the coefficient of performance of a Carnot refrigerating machine = $T_C/(T_H - T_C)$. Hence, in Fig. 369, for each $(T_H - T_C)/T_H$ heat units supplied as work to R, there will be abstracted from C: $T_C/(T_H - T_C) \times [(T_H - T_C)/T_H] = T_C/T_H$ heat units. This heat, together with the energy supplied to R as work, will be rejected by R to H. Hence, there will be rejected to H $(T_C/T_H) + [(T_H - T_C)/T_H] = 1$ heat unit. It has therefore been proved that R returns to H just as much heat as E abstracts from it; also, that R abstracts from C just as much heat as E rejects to it. Hence the quantities of heat in C and H remain unchanged by the simultaneous operations of E and R.

Now suppose for the moment that there exists some engine which has a greater efficiency than E, Fig. 369. It would be possible to use this engine to drive a Carnot refrigerating machine as indicated in Fig. 370. This engine, E_1, since it has a greater efficiency than E, Fig. 369, would convert into work a greater fraction of the heat that it abstracts from H. Hence, for each heat which E_1 abstracts from H, there would be converted into work *more than* $T_H - T_C/T_H$ heat units and there would be rejected to C *less than* T_C/T_H heat units. Also, since this engine, E_1, supplies more energy for driving R than did E, Fig. 369, it will enable R to withdraw from C more heat units than did E—*more than* T_C/T_H heat units. Thus R, Fig. 369, will reject to H the sum of the heat which it abstracts from C + the heat which it receives as mechanical energy from E_1 = (*more than* T_C/T_H) + (*more than* $T_H - T_C/T_H$) = *more than* 1 heat unit. Thus, with the arrangement of Fig. 370 more heat would be abstracted from C by R than is rejected to C by E_1, and more heat would be rejected to H by R than is abstracted from H by E_1. Hence, the net effect of the arrangement would be a steady flow of heat from C to H. But no energy has been assumed to be supplied from the outside to the arrangement of

Fig. 370 in order to cause the heat to flow from the cold body C to the hot body H. Hence it is obvious that the arrangement would be one which transfers heat from a body of low temperature to a body of higher temperature *without* the expenditure of energy from without.

The whole arrangement might be considered as a refrigerating machine which operated with *zero input*. Since such an apparatus is inconceivable and in violation of the second law of thermodynamics (Sec. 84), it follows that there must have been a fallacy somewhere in the above assumptions. The fallacy lies in the assumption of a heat engine of greater efficiency than the Carnot engine. Hence, *no heat engine can have a greater efficiency than a Carnot engine operated with the same hot and cold bodies.*

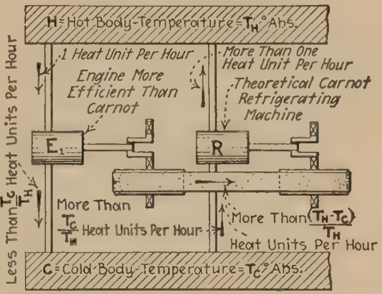

H = Hot Body-Temperature = T_H° Abs.
1 Heat Unit Per Hour
Engine More Efficient Than Carnot
More Than One Heat Unit Per Hour
Theoretical Carnot Refrigerating Machine
E_1
R
Less Than $\frac{T_C}{T_H}$ Heat Units Per Hour
More Than $\frac{T_C}{T_H}$ Heat Units Per Hour
More Than $\frac{(T_H - T_C)}{T_H}$ Heat Units Per Hour
C = Cold Body-Temperature = T_C° Abs.

FIG. 370.—Imaginary arrangement similar to that of Fig. 369 but having the Carnot refrigerating machine driven by an engine which is more efficient than the Carnot (if this were possible).

417. The Rankine Cycle Is The Standard For Vapor Heat Engines; that is, it is a theoretical cycle which can much more nearly be attained in actual practice than could a Carnot cycle. In the Carnot cycle the heating and cooling of the working substance must be effected within one cylinder (as explained in Sec. 412). A cylinder could not, however, be made of non-heat-conducting material—hence a great deal of heat would be used in heating the cylinder. Furthermore, isothermal heating and cooling would, in general, be difficult to effect. With the Rankine cycle, however, the heating and cooling of the working substance can be effected in vessels which are independent of the cylinder or machine wherein the transformation of heat energy into mechanical energy is effected. The Rankine cycle is explained below. As will be shown, its efficiency is always less than that of the Carnot cycle between the same hot and cold bodies.

EXPLANATION.—The actual steam power plant (Fig. 371) consists of a boiler, B, wherein water is heated and evaporated at constant pressure; a pipe to lead the steam from the boiler to the engine (or turbine), E; the engine (or turbine), E, wherein the steam is permitted to expand; a condenser, C, to which the steam is exhausted from E and in which the steam is condensed; and a feed pump, *P*, which forces the water into the boiler to begin a new cycle. Under ideal conditions, the processes which the water undergoes in this plant constitute the Rankine cycle. The ideal conditions are these: The steam, in passing from *B* to *E*, should undergo no loss of heat or pressure. The expansion of the steam in *E* should be isentropic (Sec. 385) and should continue until the pressure of the steam is reduced to the pressure within the condenser, *C*. The steam should be conveyed from *E* to *C* without loss of pressure. The condensed steam should leave *C* and enter *B* at the temperature of the boiling point corresponding to the pressure in *C*. Because of heat conduction into and through confining metal walls and because of friction of the steam on the walls of pipes, the actual engine does not fulfill these ideal conditions (sometimes, also, the expansion in *E* is stopped before the pressure reaches that of the condenser, see Sec. 420).

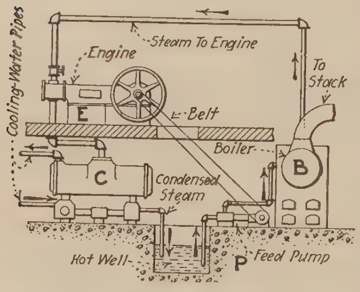


Fig. 371.—A simple steam power plant.

Explanation.—The Rankine Cycle For The Plant Of Fig. 371 May Be Pictured On The Pressure-volume Plane by the diagram *BDEF*, Fig. 372. In this diagram, *AD* represents the volume of a given weight of steam as it leaves the boiler (or superheater) and *AB* represents its volume as it enters the boiler. Hence, *BD* represents the evaporation of the water (and superheating if the steam is superheated at *D*) in the boiler. Also, the area under the line *BD* represents the external work done *in the boiler.* *DE* represents the isentropic expansion of the steam within the engine cylinder or within the turbine; hence the area under *DE* represents the work done by the steam during its expansion. Since *GE* represents the volume of the steam as it enters the condenser and *GF* represents the volume of the water as it leaves the condenser, *EF* represents the condensation of the steam in the condenser. Hence, the area under *EF* represents the external work done *on* the steam as it is forced into the condenser at constant pressure. The line *FB* represents increase in pressure that is effected in the feed pump (*P*, Fig. 372). Since water is practically incompressible, it may be said that no external work is done on the water as its pressure is increased in the feed pump. Hence, considering the entire cycle, the *net work* = (*area under BD*) + (*area under DE*) − (*area under EF*) = *area BDEF.*

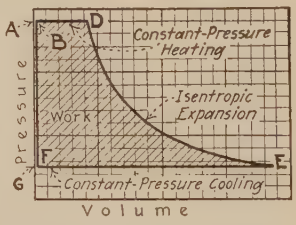
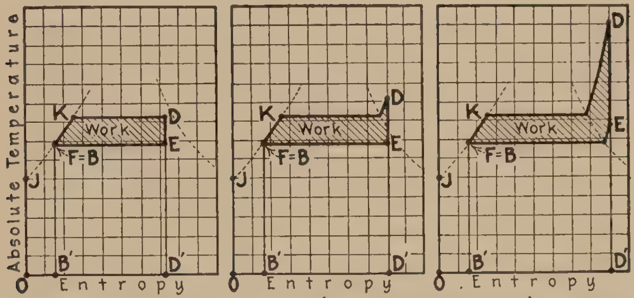


Fig. 372.—Typical pressure-volume diagram for the Rankine cycle.

EXPLANATION.—THE TEMPERATURE-ENTROPY DIAGRAM OF THE RANKINE CYCLE FOR THE PLANT OF FIG. 371 will appear as shown in Fig. 373—it will appear as shown in *I*, *II*, or *III*, depending on the condition of the steam as it leaves the boiler. The heat added in the boiler is represented by the area $B'BDD'$. The heat rejected by the condenser is represented by the area $B'BED'$. The difference between the two areas, that is the shaded area, represents the heat which is converted into work.



I-Vapor Saturated At D

II-Vapor Slightly Superheated At D

III-Vapor Highly Superheated At D

FIG. 373.—Typical temperature-entropy diagrams for the Rankine cycle. The letters correspond to those used on Fig. 372. Note that the diagram may have three distinct shapes.

418. The Indicator Diagram Of A Steam Engine Is Not The Pressure-volume Diagram Of Its Cycle.—Since the quantity of steam in a steam-engine cylinder changes from time to time, the steam does not perform a true cycle (Sec. 402) within the cylinder. The true cycle can only be analyzed by considering the entire plant as was done above. The steam performs a portion of its cycle in the cylinder, however, and the pseudo-cycle of the steam-engine cylinder can be represented by a pressure-volume diagram. When such a diagram is obtained by a recording pressure gage (an indicator, Sec. 685), the diagram is called an *indicator diagram.*

NOTE.—THE THEORETICAL INDICATOR DIAGRAM FOR THE RANKINE-CYCLE ENGINE (Fig. 374) may be drawn from values in the steam table. If the cylinder had no clearance volume (Sec. 245), the theoretical indicator diagram for the Rankine-cycle engine would appear as shown at $ADEG$, Fig. 372, in which the volume GE would then represent the displacement volume of the cylinder (Sec. 245). AD represents the *admission* of steam from the boiler. DE represents the *expansion* of the steam after the supply from the boiler has been cut off. *EG* represents the *exhausting* of the steam into the condenser. An engine cylinder with clearance would, however, perform the same functions just as well as one without clearance, provided that, on the exhaust stroke, enough steam were retained in the cylinder so that adiabatic compression of this steam into the clearence volume would return this steam to the same pressure and quality or superheat as the incoming steam from the boiler. The diagram from such a cylinder would appear as shown in Fig. 374. The line *AB* represents the volume of steam admitted to the cylinder; *CD* represents the volume of steam exhausted to the condenser.

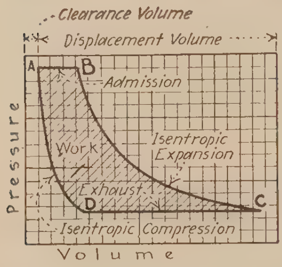


FIG. 374.—Theoretical Rankine-cycle indicator diagram for an engine with clearance.

419. The Thermal Efficiency Of The Rankine Cycle may be computed by the formula given below. This efficiency (Sec. 417) is always less than that of the Carnot cycle between the same hot and cold bodies. Since the Rankine cycle is a theoretical cycle, no vapor engine actually has an efficiency as high as that given by the following formula. But, since the Rankine cycle is the one which is closely followed by vapor engines, the efficiency value as found by For. (299) serves as standard or ultimate goal in the performance of any given engine. The formula is stated here and is derived below:

$$\mathbf{E} = \frac{\mathbf{H}_1 - \mathbf{H}_2}{\mathbf{H}_1 - \mathbf{h}_2} \qquad \text{(decimal)} \tag{299}$$

Wherein: **E** = the thermal efficiency of the Rankine cycle, expressed decimally, $\mathbf{H}_1$ = total heat of the vapor leaving the boiler (Sec. 365), in British thermal units per pound. $\mathbf{H}_2$ = the total heat of the vapor after isentropic expansion (Sec. 385) to the pressure of the condenser, in British thermal units per pound. $\mathbf{h}_2$ = the heat of the liquid at the temperature of condensation, in British thermal units per pound.

DERIVATION.—Since, by definition (Sec. 404) the thermal efficiency of a heat engine = (work done) ÷ (heat added), the efficiency may be read from Fig. 373. In Fig. 373, work done = area *BKDE;* and heat added = *B′BKDD′*. Hence,

$$\mathbf{E} = \frac{Area\ BKDE}{Area\ B'BKDD'} \qquad \text{(decimal)} \tag{300}$$

Now, *area OJKDD'* = $\mathbf{H}_1$; *area OJBED'* = $\mathbf{H}_2$; and, *area OJBB'* = $\mathbf{h}_2$. Also,

(301) $$Area\ BKDE = (area\ OJKDD') - (area\ OJBED') \qquad \text{(area)}$$

or, by substitution,

(302) $$Area\ BKDE = \mathbf{H}_1 - \mathbf{H}_2 \qquad \text{(area)}$$

Likewise,

(303) $$Area\ B'BKDD' = (area\ OJKDD') - (area\ OJBB') \qquad \text{(area)}$$

or, by substitution,

(304) $$Area\ B'BKDD' = \mathbf{H}_1 - \mathbf{h}_2 \qquad \text{(area)}$$

Hence, by substituting from (302) and (304) into (300), there results:

(305) $$\mathbf{E} = \frac{\mathbf{H}_1 - \mathbf{H}_2}{\mathbf{H}_1 - \mathbf{h}_2} \qquad \text{(decimal)}$$

which is the same as For. (299).

EXAMPLE.—What would be the Rankine-cycle efficiency for a steam power plant in which the boiler delivers steam, of 95 per cent. quality, to the prime mover at 125 lb. per sq. in. abs. and in which the condenser pressure is 2 lb. per sq. in. abs.? SOLUTION.—From the heat-entropy chart of Fig. 343, $\mathbf{H}_1$ = 1,147 and $\mathbf{H}_2$ = 888 *B.t.u. per lb.* Also, from Steam Table 394, $\mathbf{h}_2$ = 94 *B.t.u. per lb.* Hence, by For. (299), the *efficiency* = $\mathbf{E} = (\mathbf{H}_1 - \mathbf{H}_2)/(\mathbf{H}_1 - \mathbf{h}_2) = (1{,}147 - 888) \div (1{,}147 - 94) = 0.246$, or 24.6 *per cent.*

EXAMPLE.—What would be the efficiency of a Carnot cycle between the same temperatures as the preceding example? SOLUTION.—From the steam table, the temperature of the steam leaving the boiler = 344.4° F., and the temperature of condensation = 126.15° F. Hence, by For. (292), the *Carnot efficiency* = $\mathbf{E} = (\mathbf{T}_H - \mathbf{T}_C)/\mathbf{T}_H = (344.4 - 126.15) \div (344.4 + 460) = 0.272$, or 27.2 *per cent.*

420. The "Theoretical Steam-engine Cycle" (Fig. 375) differs from the Rankine cycle for several reasons: (1) In actual engines the steam is hardly ever expanded until the pressure within the cylinder reaches the condenser pressure because this would necessitate a very large cylinder volume and such a large volume would occasion large frictional and thermal losses which would overbalance the additional work which would be obtained by the continued expansion to condenser pressure. Thus, in actual engines, the work area *GCH*, Fig. 375, is *intentionally* not used or is "lost." The maximum loss from this source occurs in the non-expansive engine, (Figs. 359 and 360) in which the steam is released from the cylinder at practically supply pressure. (2) For the same reasons as in (1) and to provide smoother operation, the compression of the steam (after the exhaust valve is closed) is hardly ever carried to boiler pressure. Compression is begun later in the stroke than shown in Fig. 374—more as shown at *DE*, Fig. 375. The incoming steam must therefore help to fill the clearance volume—this entails a loss as shown by the area *EAF*, Fig. 375, which is also usually *intentional*. Hence, the indicator diagram *FBGHDE*, Fig. 375, represents the theoretical steam-engine *pseudo*-cycle. This cycle is sometimes called the *modified Rankine cycle.* It is not convenient to draw either the pressure-volume or the temperature-entropy diagrams of the *true steam-engine cycle.*

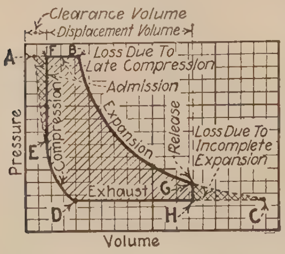


FIG. 375.—Theoretical steam-engine indicator diagram showing losses due to incomplete expansion and late compression

NOTE.—THE ACTUAL STEAM-ENGINE INDICATOR DIAGRAM differs from the theoretical because of unavoidable losses, the principal losses being:

(1) *Loss due to steam friction* as the steam flows through the supply and exhaust pipes and through the valves of the engine.

(2) *Loss due to heat absorbed and liberated by the metal cylinder and piston.* The parts of the engine with which the steam contacts will tend to follow and attain the temperature of the steam. Certain parts of the engine, the valves and pipes, will always be in contact with steam at practically the same temperature—hence, after the engine has been operating for a short while, these parts will no longer absorb heat from the steam. The piston and cylinder, however, are exposed to the steam as it expands—hence, as the steam-temperature rises and falls, the temperature of the walls will tend to rise and fall too. When steam from the boiler enters the cylinder, it will give up a portion of its heat to the cylinder walls and piston. After the steam has expanded somewhat, its temperature will be less than that of the walls and it will then absorb the heat from them. Thus there is a continual interchange of heat between the steam and the cylinder and piston. This heat interchange occasions a loss of energy.

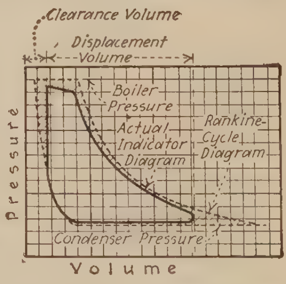


FIG. 376.—A typical steam-engine indicator diagram superimposed on a theoretical Rankine-cycle diagram to show where the losses (shaded) occur.

(3) *Loss due to radiation.* The steam is, from the time it leaves the boiler until it is exhausted by the engine, within bodies which cannot be

well enough insulated to prevent the flow of heat through them. A small amount of heat is lost in this way. The sum of the losses due to the above causes and due to the difference between the theoretical steam-engine cycle and the Rankine-cycle is shown by the shaded area on Fig. 376.

421. Steam Engines May Be Operated As Air Engines if they are supplied with air under pressure instead of with steam. The theoretical indicator diagram for an air engine appears almost the same as shown in Fig. 375, the chief difference being that the expansion line *BG* has a slightly different slope. Such air engines are not generally suitable for power purposes because of the difficulty of supplying compressed air. For certain uses, however, such as portable tools, air engines are extensively used. They have the advantage that they may be supplied with air from a compressor at a great distance without very large loss through the piping (in cases where much steam would condense).

Note.—Strictly, These Air Engines Are Not Heat Engines because, with them, the heat energy which is supplied them does not come from a natural source of heat but from mechanical energy expended in compressing the air. Air engines have been built which were supplied with heat from a natural source (a fuel) but they have lately been replaced by internal-combustion engines (following sections)

422. The Otto Cycle, so called, is a pseudo-cycle which is employed in most of the present internal-combustion engines. It was devised in 1862 as a cycle the operations of which were to be carried out in four strokes of a piston within a cylinder as explained below. It has since been applied to engines wherein two of the four processes are performed simultaneously as explained in Sec. 539. Until the invention of the Diesel engine (Sec. 547), the Otto cycle provided the most efficient internal-combustion engine known.

Explanation.—The Theoretical Pressure-volume (Or Indicator) Diagram Of The Otto Cycle is shown in Fig. 377. *AB* represents the suction stroke during which a charge of combustible gas and air is drawn into the cylinder at atmospheric pressure. *BC* represents the compression of the charge (adiabatically) into the clearance volume. At *C* the charge is ignited by a spark causing an explosion or constant-volume heating *CD*. The heated gases then expand adiabatically, forcing the piston away from the closed end of the cylinder—process *DE*.

A valve then opens the cylinder to the atmosphere and permits the gases to escape—process EB. The piston is then moved toward the closes end of the cylinder and forces the greater portion of the remaining gases into the atmosphere through the open exhaust valve—process BA. The cycle is thus completed. For two strokes of the piston, AB and BA, the pressure on the piston is atmospheric. Hence the work done by the piston in exhausting the gases is balanced by the work done on the piston by the incoming gases during suction—the net work for these two strokes is zero.

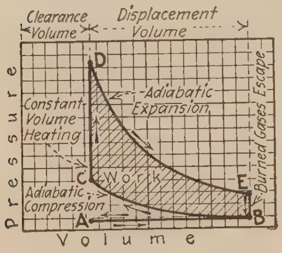


Fig. 377.—Typical pressure-volume or indicator diagram of the theoretical Otto cycle.

During the compression stroke, BC, the piston does work on the gases as represented by the area under BC. During the expansion stroke the gases do work on the piston as represented by the area under DE. Processes CD and EB, since they are constant-volume processes, represent no work. Hence, the net work of the cycle is the difference between that done during the expansion and compression strokes, or as represented by the area $BCDE$. The actual construction and operation of Otto-cycle engines will be explained in Div. 16.

From the standpoint of heat added and work done, the cycle is the same, as can be shown, as if the gas were heated and cooled *within the cylinder* so as to produce the effects CD and EB. Hence, the pseudo-cycle is exactly equivalent to a true cycle which would be represented by the same pressure-volume diagram (Fig. 377).

423. The Thermal Efficiency Of The Theoretical Otto Cycle may readily be computed from the energy relations given in Div. 8. The net work of the cycle is the differents between the work done during the two adiabatic processes. The heat is added only along the process CD (Fig. 377). By writing the energy relations for these processes, it may be found that the efficiency of the cycle is given by the following formulas:

$$\mathbf{E} = 1 - \frac{\mathbf{T}_B}{\mathbf{T}_C} = 1 - \frac{\mathbf{T}_E}{\mathbf{T}_D} \qquad \text{(decimal)} \tag{306}$$

$$\mathbf{E} = 1 - \left(\frac{V_C}{V_B}\right)^{\mathbf{k}-1} \qquad \text{(decimal)} \tag{307}$$

$$\mathbf{E} = 1 - \left(\frac{P_B}{P_C}\right)^{\frac{\mathbf{k}-1}{\mathbf{k}}} \qquad \text{(decimal)} \tag{308}$$

Wherein: $\mathbf{E}$ = the thermal efficiency of the cycle, expressed decimally. $\mathbf{T}$ = absolute temperature, in any unit. V =

volume, in any unit. P = absolute pressure, in any unit. The subscripts denote points of Fig. 377. Thus, $\mathbf{T}_B$ = the absolute temperature of the gas at B, Fig. 377. $\mathbf{k}$ = the ratio of the specific heats of the gases ($\mathbf{C}_P/\mathbf{C}_V$) and is generally taken as 1.4.

Example.—What is the theoretical efficiency of an Otto-cycle gas engine if the gas is compressed to 90 lb. per sq. in. abs. when explosion occurs? (Take $\mathbf{k} = 1.4$.) Solution.—By For. (308), the *efficiency* = $\mathbf{E} = 1 - (P_B/P_C)^{\frac{\mathbf{k}-1}{\mathbf{k}}} = 1 - (14.7 \div 90)^{\frac{1.4-1}{1.4}} = 0.404$, or 40.4 *per cent.*

424. The Diesel Cycle, so called, is a pseudo-cycle of recent invention upon which internal-combustion engines can be made to operate and which gives higher efficiencies than does the Otto cycle. The Diesel engine is particularly adapted to the combustion of heavy oils. It is a four-stroke cycle like the Otto but differs in the method of introducing and igniting the fuel. The operation and construction of commercial Diesel-cycle engines is explained in Sec. 547. An explanation of the cycle is given below.

Explanation.—The Theoretical Pressure-volume Or Indicator Diagram Of The Diesel Cycle is shown in Fig. 378. Line AB represents the suction stroke during which atmospheric air is drawn into the cylinder. Line BC represents the adiabatic compression of this air into the small clearance volume. The temperature of the air at C, where the pressure is about 500 lb. per sq. in., is very high. Oil is then forced into the cylinder and, due to the high temperature of the air, immediately ignites and burns. The shape, on the pressure-volume diagram, of the line which represents the burning of the oil depends on the rates of oil admission and piston movement. The process may be (1) one of constant pressure, as CE, (2) one of constant pressure and constant temperature, as CDF, or (3) one of constant temperature throughout the entire burning, as CG (see Fig. 485 for actual Diesel-engine indicator diagram). After the oil admission is stopped, as at E, F, or G, Fig. 378, the burned gases are allowed to expand adiabatically to H where an

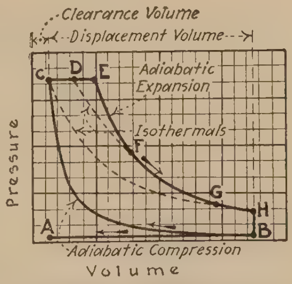


Fig. 378.—Pressure-volume or indicator diagram of the theoretical Diesel engine.

exhaust valve is opened and the pressure immediately drops to atmospheric. On the return stroke of the piston the burned gases are exhausted to the atmosphere—process *BA*—and the engine is then ready to begin another cycle. As with all cycles, the net work is represented by the area enclosed by the lines of the pressure-volume diagram.

425. The Thermal Efficiency Of The Theoretical Diesel Cycle may be computed by applying the energy-relation formulas for gases as given in Div. 8. The efficiency depends on the pressures, volumes, and temperatures of the gases at different points during the cycle and on the nature of the burning process; that is, whether the oil is burned at constant pressure, constant temperature, or in some intermediate manner. *For constant-pressure burning*, the efficiency can be shown to be:

$$\text{(309)} \qquad \mathbf{E} = 1 - \frac{1}{\mathbf{k}}\left(\frac{\mathbf{T}_H - \mathbf{T}_B}{\mathbf{T}_E - \mathbf{T}_C}\right) \qquad \text{(decimal)}$$

Wherein: **E** = the thermal efficiency of the cycle, expressed decimally. **k** = the ratio of the specific heats of the gases ($\mathbf{C}_P/\mathbf{C}_V$) and is generally taken as 1.4. $\mathbf{T}_H$, $\mathbf{T}_B$, $\mathbf{T}_E$, and $\mathbf{T}_C$ = respectively the absolute temperatures of the gases at points *H*, *B*, *E*, and *C* (Fig. 378), in any unit provided all are in the same unit.

Example.—If the temperatures at points *B*, *C*, *E*, and *H* (Fig. 378) are, respectively, 130, 1,160, 2,980, and 1,180° F., what is the theoretical efficiency of the cycle? (Take **k** = 1.4). Solution.—By For. (309), the *efficiency* $= 1 - [(1/\mathbf{k}) \times (\mathbf{T}_H - \mathbf{T}_B)/(\mathbf{T}_E - \mathbf{T}_C)] = 1 - [(1 \div 1.4) \times (1{,}180 - 130) \div (2{,}980 - 1{,}160)] = 0.549$, or 54.9 *per cent.*

426. All Compressors (Fig. 379) operate on a pseudo-cycle which is explained below and in succeeding sections. Although this pseudo-cycle is generally called *the air-compressor cycle*, it is actually the cycle of all gas and vapor compressors. A *compressor*, in general, is a machine by which a gaseous substance is transferred from a vessel of low pressure to one of higher pressure. A compressor is an essential part of practically every refrigerating machine.

Explanation.—Operation Of A Compressor With No Clearance.—Consider first a cylinder and piston so constructed as to have no clearance volume (Sec. 245). Starting with the piston against the cylinder head, let the piston be drawn away from the head while a valve (in the head) is open. Air (or some other gaseous substance) will be drawn into the cylinder through the open valve. Assume that the air (or gas) is drawn from a large vessel so that the pressure is constant during the time that the air is drawn into the cylinder. This process may be represented by the line *AB* (Fig. 380). Let the valve through which the air entered be then closed and let the piston be moved back toward the cylinder head. The gas will be compressed. If no heat is added to or abstracted from the air, the compression will be adiabatic, *BC* Fig. 380, and the temperature will rise. When the pressure in the cylinder becomes equal to that in the vessel into which the air is to be transferred, let another valve be opened so that further movement of the piston toward the head will expel the air from the cylinder into the high-pressure vessel. If the vessel is large, the pressure during this discharge will remain practically constant as at *CD*, Fig. 380. As soon as the piston is again moved from the head, it will draw in a new charge of air from the low-pressure vessel and thus begin a new cycle. Before a new charge can be drawn in, however, the pressure in the cylinder will fall to that of the lower-pressure vessel—process *DA*, Fig. 380.

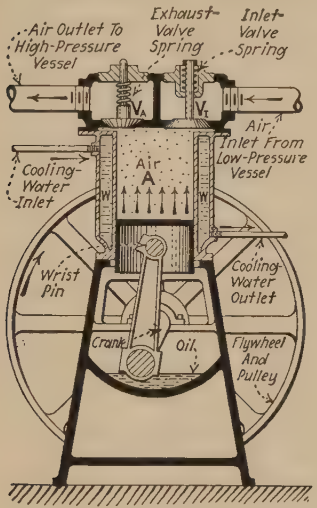


FIG. 379.—A simple air compressor. Water, *W*, must be circulated around the cylinder to keep it cool.

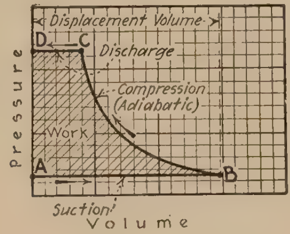


FIG. 380.—Pressure-volume diagram for theoretical air compressor with zero clearance and adiabatic compression.

427. All Actual Compressors Have Clearance.—Since it is infeasible, practically, to attempt the construction of a compressor without some linear distance between the cylinder end and the piston when it is at the end of its stroke, all actual compressors must be somewhat different in their operation from that described in Sec. 426.

EXPLANATION.—OPERATION OF A COMPRESSOR WITH CLEARANCE.—A certain volume of air, *GF* Fig. 381, will because of the clearance, remain within the cylinder at the end of the discharge process. Then, if the valve connecting the cylinder with the low-pressure vessel were immediately opened, this air would flow into the low-pressure vessel. It is better to keep the valve closed and permit the high-pressure air in the clearance volume (at *F*, Fig. 381) to expand adiabatically within the cylinder until its pressure is reduced to that of the low-pressure vessel, *FA* Fig. 381. If the valve to the low-pressure vessel is then opened, air will be drawn into the cylinder for the remainder of the piston's stroke. Thus, a volume of air *AB*, which is less than the displacement volume (Sec. 245), is drawn into the cylinder. The volume *AB*, Fig. 381, is called the *low-pressure capacity* of the compressor. Hence, to transfer the same weight of air per cycle, volume *AB*, Fig. 381, must equal volume *AB*, Fig. 378, or—the displacement volume must be greater for the compressor with clearance.

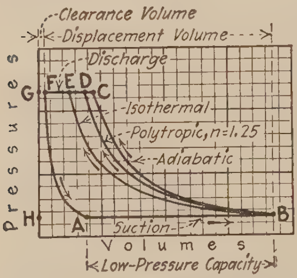


Fig. 381.—Theoretical indicator diagram for air-compressor with clearance.

428. The Volumetric Efficiency Of A Compressor may be defined as the ratio of the low-pressure capacity (Sec. 427) to the displacement volume. Expressed as a formula:

$$\text{(310)} \quad \textit{Volumetric efficiency} = \frac{\textit{Low-pressure capacity}}{\textit{Displacement volume}} \quad \text{(decimal)}$$

Example.—If, in Fig. 381, the length $AB = 1$ in. and the displacement volume is represented by 1.2 in., what is the volumetric efficiency of the compressor? Solution.—By For. (310), the *Volumetric efficiency* = (*Low-pressure capacity*)/(*Displacement volume*) $= 1.0 \div 1.2 = 0.833$, or 83.3 *per cent?*

429. The Work Required To Operate A Compressor Is Independent Of The Clearance Of The Compressor—that is, for a given weight of air, the same pressures, and the same kind of compression (see below), the work required is the same for a compressor with clearance as for one without clearance. The work is represented by the areas *ABCD* Fig. 380 and *ABCF* Fig. 381. The work done on the air, in either case, remains within the discharged air as heat energy.

Explanation.—The Effect Of The Compression Curve On The Work Of A Compressor will now be analyzed. In many instances the discharged air is stored for a long time or piped a great distance before it is employed. When this is done, the air generally is cooled and very frequently it is cooled to the temperatue of the low-pressure vessel. When this occurs, the volume of high-pressure air is decreased from *FC*, Fig. 381, to *FE*. That is, for every *FC* cu. ft. delivered by the compressor, only *FE* cu. ft. appear where the air is being used. This naturally raises a question as to whether it would not be better to compress the air isothermally instead of adiabatically. If, in Fig. 381, the compression were isothermal, *BE*, instead of adiabatic, *BC*, the work area of the cycle would be *ABEF* instead of *ABCF*. Hence, much less work would be required if the compression were isothermal. To secure isothermal compression, however, heat must be abstracted from the air, during the compression, as fast as work is done on the air. The customary way of abstracting heat is by jacketing the compressor cylinder with flowing water (*W* Fig. 379). By so doing, however, enough heat cannot, in practical machines, be abstracted to produce isothermal compression. The general result is a polytropic compression (Sec. 273) about as shown by *BD*, Fig. 381. The saving due to the water jacket is therefore the area *DCB*.

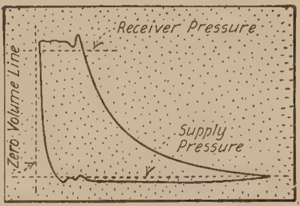


Fig. 382.—Typical air-compressor indicator diagram.

Note.—Actual Compressor Diagrams Differ From The Theoretical (Fig. 382). Since actual compressors are generally made with valves, *V* (Fig. 379) which are automatically opened and closed by the differences of pressure on their two sides (Fig. 379), and since these valves must be fitted with springs to insure their rapid closure, the pressure of the air within the cylinder during the suction stroke (*AB*, Fig. 381) will always be less than that of the low-pressure vessel and the pressure within the cylinder during discharge will always be greater than that of the high-pressure vessel (see Fig. 382).

430. Compound, Or Staged, Compressors are those in which the gaseous substance passes through more than one cylinder in having its pressure raised from that of the low-pressure vessel to that of the high-pressure vessel. When the ratio of pressures (*absolute discharge pressure* ÷ *absolute supply pressure*) of a compressor is greater than 6, compressors are generally made compound. That is, the gas is first compressed in one cylinder to some pressure intermediate between discharge and supply pressures, is then cooled in a suitable vessel called an *intercooler*, and is then further compressed in a second compressor cylinder. Sometimes a second intercooler and a third compressor cylinder are employed—the compressor is then termed *three stage.* A compressor which employs two cylinders and one intercooler is termed *two-stage.* A two-stage compressor is shown in Fig. 483. The *object* of compounding compressors is two-fold: (1) *The volumetric efficiency of compounded compressors is greater than that of single-stage compressors.* (2) *Compounded compressors require less work for delivering a given quantity of gas (or vapor) between given pressures than do single-stage compressors.* See explanation below.

Explanation.—The Theoretical Indicator Diagram For A Single-stage Compressor without clearance is shown in Fig. 383 by *AFPL.* If the compression could be made isothermal it would be represented by *PD* and the saving in work over polytropic compression would be represented by the area *DFP.* If two-stage compression is desired, however, the polytropic compression would be stopped at a point *K*, and the compressed substance would be discharged (*KG*) at this pressure into an intercooler. Here the substance would be cooled to the temperature which it had when at *P.* Hence, when the substance is drawn into the high-pressure cylinder, its volume would be only *GJ.* When further compressed, the compression will again be polytropic and will be represented by *JE.* The temperature of the substance at *E* will be less than at *F* with single-stage compression. The work done in the high-pressure or second-stage cylinder is represented by the area *AEJG.* That done in the low-pressure or first-stage cylinder is represented by the area *GKPL.* Hence, a saving in work is effected by compounding as is represented by the area *EFKJ* (shaded).

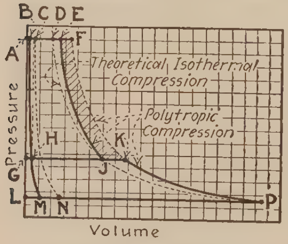


Fig. 383.—Theoretical indicator diagram showing benefits of compound compression.

431. Concerning Volumetric Efficiencies Of Compound Compressors: Assume that the single-stage compressor can be made with a clearance volume as small as *AC* (Fig. 383). The substance compressed in this volume will expand along *CN.* The low-pressure capacity will then be *NP.* Now, the same cylinder, if used as the low-pressure cylinder of the two-stage compressor would have a clearance expansion line *HM* and a correspondingly large low-pressure capacity *MP.* The high-pressure cylinder, being of much smaller size than the low-pressure cylinder can be constructed with a proportionally smaller clearance volume, *AB.* Besides requiring less work and having greater volumetric efficiencies than single-stage compressors, *compounded compressors generally have higher mechanical efficiencies* and suffer less leakage past the pistons.

NOTE.—THE PROPER INTERCOOLER PRESSURES FOR COMPOUND COMPRESSORS, when intercooling reduces the temperature of the compressed gas to that at which the gas enters the first stage, are such that the ratio of pressures is the same for each of the several cylinders. Hence, for a two-stage compressor:

$$P = \sqrt{P_1 P_2} \qquad \text{(pressure)} \tag{311}$$

Wherein: P = absolute pressure in intercooler. P_1 and P_2 = respectively, the absolute suction and delivery pressures. All pressures must be measured in the same units.

432. A Practical Refrigerating-machine Cycle, In Which The Working Substance Is Gaseous Throughout The Cycle, is explained below. Because air, being the most easily obtained gas, is generally used in this cycle, it is usually spoken of as the *cycle of the air refrigerating machine.*

EXPLANATION.—The apparatus of an air refrigerating machine is shown in Fig. 384. The compressor, C, delivers air through a cooling coil, D, wherein the air is cooled by circulating water, to the lowest possible temperature. From D the air passes to an air engine, E, usually called an *expander,* where the air does work on a piston and simultaneously has its temperature reduced. The work done by the expanding air in E is utilized to drive the compressor; but, since it is insufficient for this purpose, must be complemented by work from an external source such as the motor, M. The expanded air from E passes through an exhaust pipe A into the refrigerated space R. After being warmed by the absorption of heat in R, the air is withdrawn at B and reenters C for a new cycle. The pressure of

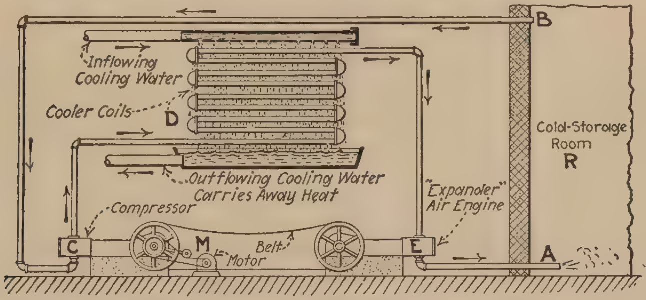


FIG. 384.—Typical equipment for a low-pressure air refrigerating machine.

the air in R must, for practical reasons, be atmospheric. Although this method is quite practical, it requires a compressor and expander of very large cubical capacity. A slight modification permits the use of much smaller compressor and expander. Openings A and B (Fig. 384) are generally connected to a pipe coil—a cooling coil—of large external area. The apparatus is then so operated in starting that the air in this coil is compressed to a moderate pressure. The refrigerating cycle is then the same as above described except that the air is, at all points, under much greater pressure and hence has a much greater density. This apparatus is called a *dense-air* refrigerating machine (Fig. 566).

EXPLANATION.—THE PRESSURE-VOLUME RELATIONS (INDICATOR DIAGRAMS) OF THE GAS REFRIGERATING-MACHINE cycle are shown in Fig. 385. Clearances are neglected. FD represents the suction stroke of the compressor, DC the compression stroke, and CA the discharge stroke. AB represents the admission stroke of the expander, BE the expansion stroke, and EF the exhaust stroke. Hence, area $ACDF$ represents the work required to drive the compressor and area $AB EF$ represents the work done by the expander. The difference, or $BCDE$ represents the work which must be supplied from an external source (M in Fig. 384). The cycle is, in effect, the same as if the air were compressed in C (Fig. 384), cooled in D, expanded in E, and heated in R as shown by the diagram $DCBE$ (Fig. 385). This is actually the true cycle (Sec. 402).

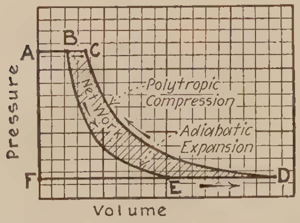


FIG. 385.—Theoretical indicator diagram of a gas refrigerating-machine cycle.

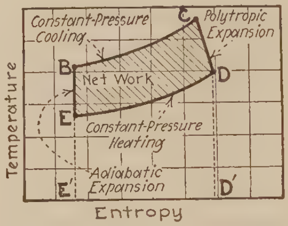


FIG. 386.—Temperature-entropy diagram (not to scale) of the air-refrigerating-machine cycle; Figs. 384 and 385.

EXPLANATION.—THE TEMPERATURE-ENTROPY DIAGRAM OF THE TRUE GAS REFRIGERATING-MACHINE CYCLE is shown in Fig. 386. The heat abstracted from the "cold body" is represented by the area $E'EDD'$. The heat equivalent of the net work of the cycle is represented by the area $BCDE$. The heat rejected to the "hot body" is represented by the area $E'BCDD'$.

433. The Vapor-refrigerating-machine Cycle is that which is employed in most practical refrigerating plants (see Div. 18). In this cycle the working substance is made to undergo changes of state—it is liquid at certain times and gaseous (vapor) at other times. Because of the large latent heat of vaporization of certain liquids which are used, the machines employed in this cycle can be made much smaller for a given service than could gas refrigerating-machines. The cycle is explained below. The actual machines and processes are described more fully in Div. 18.

Explanation.—A simple vapor refrigerating plant is illustrated in Fig. 387. Assume the compressor, *C*, to be supplied with ammonia vapor at a low temperature and pressure. The vapor will leave the compressor at a higher temperature and pressure. Let the pressure be high enough that the corresponding boiling point is higher than the temperature of water from some nearby natural source such as a stream or a well. If this water is passed over the pipes through which the compressure discharges, as in the condenser *B*, the vapor inside the pipes will be cooled by the water to its boiling point and will also be condensed. If enough water is supplied to *B*, the condensed vapor will be cooled below its boiling point. The pressure in the coils of *B* will remain constant because more hot vapor is supplied by the compressor as fast as the vapor in the coils is condensed and permitted to flow from the coils through the valve *V*. From *V*, the working substance is permitted to flow into coils *E* where a low pressure is maintained. In passing through *V*, therefore, the warm liquid suffers a throttling expansion (Sec. 387) and enters *E* as a very wet vapor at low pressure. The temperature of the wet vapor is very low because of its low pressure. Heat will pass through the coils *E* to the vapor inside and will cause vaporization of the liquid portion of the vapor. Heat will thus be absorbed by the vapor from the room *R*. Until the vapor becomes dry, its temperature will remain constant, because the pressure in the coils is maintained constant, as explained below. Should the vapor be permitted to remain within

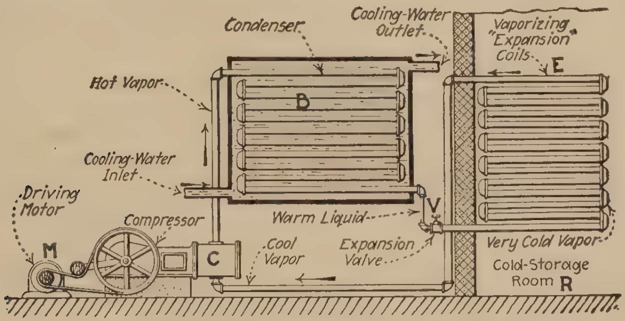


Fig. 387.—A simple vapor refrigerating plant.

the coil *E* after it is completely vaporized, it may become superheated. The pressure in the coil is maintained constant by removing vapor with the compressor *C* as fast as it is admitted through *V* and is vaporized. The vapor that is removed by *C* is compressed and repeats its passage through the system.

Explanation.—The Pressure-volume Diagram Of The Vapor-refrigerating-machine Cycle (Fig. 388) is very similar to that of the theoretical Rankine cycle (Fig. 372). If *C* (Fig. 388) represents the pressure and volume of a given weight of vapor as it enters the compressor, *C*, Fig. 387, then *CD* represents its compression in the compressor, *DA* represents its condensation in the condenser, *AB* represents the reduction of pressure and increase in volume as the vapor passes through the expansion valve, *V*, Fig. 387, and *BC* represents the vaporization of the liquid in the expansion coil, *E*, Fig. 387. Since the process *AB* (Fig. 388) is a throttling expansion, the area under *AB* does not represent work done and the area *ABCD* does not represent the net work of the cycle. The net work may, however, be found from the indicator diagram of the compressor which will appear as shown in Fig. 381.

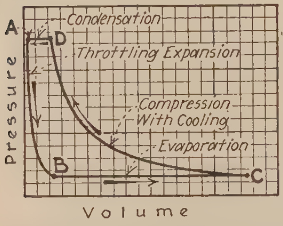


Fig. 388.—Pressure-volume diagram of the vapor refrigerating cycle.

Explanation.—The Temperature-entropy Diagram Of The Vapor-refrigerating-machine cycle will vary in appearance with the condition of the vapor as it enters the compressor—whether wet, dry, or superheated—and with the temperature at which the liquid reaches the expansion valve. If the vapor entering the compressor is in the dry-saturated condition and reaches the expansion valve at a temperature intermediate between those of condensation in *B* (Fig. 387) and vaporization in *E*, then the temperature-entropy diagram will appear as shown in Fig. 389. In Fig. 389, *CD* represents the compression of the vapor, *DEFA* represents the cooling in the condenser, *AB* represents the throttling expansion through the valve, and *BC* represents the vaporization in the expansion coils. The area *B'BCC'* represents the heat abstracted from the cold body (*R*, Fig. 387), area *D'DCC'* represents the heat rejected to the compressor cooling water, area *A'AFEDD'* represents the heat rejected to the condenser cooling water, and area *A'ABB'* has no real significance.

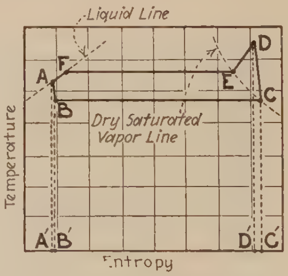


Fig. 389.—Typical temperature-entropy diagram of a vapor-refrigerating-machine cycle.

434. The Indicated Work Of A Heat Engine Or Refrigerating Machine is the mechanical work that is expended by or on the working substance within the cylinder. It is the work that is measured by the indicator (Sec. 684) diagram which is taken from the cylinder (see Secs. 503, 504 and 549 for methods of computing indicated work). For heat engines, the indicated work is always more than the work which is actually available at the engine shaft for useful purposes. For refrigerating machines, the indicated work is always less than the work which must be supplied at the compressor shaft. The difference between the indicated work and the shaft input or output is due to the loss of energy within the machine due to the friction of its parts. The ratio of the shaft output of a heat engine to its indicated work is called its *mechanical efficiency*. The ratio of the indicated work of a compressor (or refrigerating machine) to its shaft input is likewise called its *mechanical efficiency*.

NOTE.—THE INDICATED WORK OF PURELY ROTATIVE MACHINES CANNOT BE MEASURED.—Examples of purely rotative machines are the steam turbine and the turbo-compressor. Since these machines do not employ pistons in cylinders, no indicator diagrams can be obtained from them. The mechanical efficiency of such machines cannot ordinarily be found.

435. The Losses In Heat Engines may now be summarized. It was shown in Sec. 416 that no heat engine could have a greater efficiency than the Carnot—that is, that no heat engine could convert into heat more than a certain fraction of the heat supplied to it.

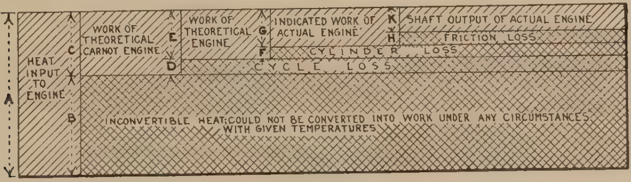

HEAT INPUT TO ENGINE
A
B
C
WORK OF THEORETICAL CARNOT ENGINE
E
D
WORK OF THEORETICAL ENGINE
G
F
INDICATED WORK OF ACTUAL ENGINE
K
H
SHAFT OUTPUT OF ACTUAL ENGINE
FRICTION LOSS
CYLINDER LOSS
CYCLE LOSS
INCONVERTIBLE HEAT; COULD NOT BE CONVERTED INTO WORK UNDER ANY CIRCUMSTANCES WITH GIVEN TEMPERATURES

FIG. 390.—Showing why heat-engines have low efficiencies. Only the vertical distances —not the areas—are significant.

EXPLANATION.—The heat energy supplied to an engine (*A*, Fig. 390) may be first divided into two parts—*C*, that which the theoretical ideal engine could convert into work, and *B*, that which could not be converted into work by even the most perfect engine. C and B are therefore termed the *available* and *unavailable heat*, respectively. Now, since heat engines do not generally operate on cycles which are even theoretically as efficient as is the Carnot, it follows that such engines would not provide even theoretically as much work from a given heat input as does the Carnot. Hence, some such portion as E, Fig. 390, of the supplied heat, A, would be convertible into work by the theoretical engine, whereas a portion D is rejected along with B, that rejected by the Carnot engine. Then, since no actual engine can be made to actually follow its perfect cycle, the indicated work (Sec. 434) G, will always be less than the work, E, of the theoretical engine. The difference, F, is the loss due to imperfections (from the heat standpoint) of the engine construction.

Finally, the work output of the engine at its shaft (K, Fig. 390) will always be less than its indicated work G. The difference, H, is the loss due to imperfections (from the mechanical standpoint) of the engine construction—it is the loss due to friction between parts of the engine. Hence, of the heat, A, supplied to the engine only a small fraction, K, can really be utilized. The remainder $(B + D + F + H)$ is rejected (sometimes said to be "lost"); it is not really lost in the sense that it is destroyed but in the sense that it cannot any longer be converted into mechanical energy or work.

436. Various Heat-engine-efficiency Expressions May Be Defined By Means Of Fig. 390 Thus:

$$(312)\quad \textit{Carnot efficiency} = \frac{\textit{Work of theoretical Carnot engine}}{\textit{Heat input}} = \frac{\textit{Quantity } C}{\textit{Quantity } A} \quad \text{(decimal)}$$

$$(313)\quad \textit{Theoretical efficiency} = \frac{\textit{Work of theoretical engine}}{\textit{Heat input}} = \frac{\textit{Quantity } E}{\textit{Quantity } A} \quad \text{(decimal)}$$

$$(314)\quad \textit{Actual thermal efficiency} = \frac{\textit{Indicated work}}{\textit{Heat input}} = \frac{\textit{Quantity } G}{\textit{Quantity } A} \quad \text{(decimal)}$$

$$(315)\quad \textit{Overall efficiency} = \frac{\textit{Shaft output}}{\textit{Heat input}} = \frac{\textit{Quantity } K}{\textit{Quantity } A} \quad \text{(decimal)}$$

$$(316)\quad \textit{Type efficiency} = \frac{\textit{Work of theoretical engine}}{\textit{Work of theoretical Carnot engine}} = \frac{\textit{Quantity } E}{\textit{Quantity } C} \quad \text{(decimal)}$$

(317) *Cylinder* (or *practical*) *efficiency* =

$$\frac{\textit{Indicated work}}{\textit{Work of theoretical engine}} = \frac{\textit{Quantity } G}{\textit{Quantity } E} \quad \text{(decimal)}$$

(318) $$\textit{Mechanical efficiency} = \frac{\textit{Shaft output}}{\textit{Indicated work}} = \frac{\textit{Quantity } K}{\textit{Quantity } G} \quad \text{(decimal)}$$

NOTE.—THE THEORETICAL EFFICIENCY OF A HEAT-ENGINE, as given by For. (313) above, is the efficiency of its theoretical cycle such as the Rankine, Otto, or Diesel. Theoretical efficiencies of these cycles are given by Fors. (299), (308), and (309).

EXAMPLE.—See Prob. 18 at end of this division.

QUESTIONS ON DIVISION 12

1. Define a *cycle*. What is the distinction between a *true cycle* and a *pseudo cycle?*

2. What is the object of employing diagrams in the study of cycles? What diagrams are usually employed?

3. Define a *heat engine*. A *refrigerating machine*. What other descriptive name may be given to a refrigerating machine?

4. What are the three essential elements of every heat engine and refrigerating machine? What happens between these elements in the operation of a heat engine? In the operation of a refrigerating machine?

5. Define the *efficiency* of a heat engine. Express the definition as a formula. Is a high or low value of engine efficiency desirable?

6. Define the *coefficient of performance* of a refrigerating machine. Express the definition as a formula. Is it desirable that the coefficient of performance of a refrigerating machine be high or low?

7. Explain the operation of the simple non-expansive engine. Explain the construction of the pressure-volume diagram of its cycle.

8. What kind of figures always result when the pressure-volume or temperature-entropy diagrams of cycles are plotted?

9. Draw a sketch of the apparatus which must be employed with the non-expansive steam engine to make up a true cycle.

10. Draw the temperature-entropy diagram of a non-expansive steam engine and explain its construction. Modify the diagram so that it represents an equivalent cycle without frictional processes. Explain the significance of the various areas on the diagram.

11. What was the purpose of devising the *Carnot* cycle? Are engines built to operate on this cycle? Why?

12. Explain the construction and operation of the Carnot heat engine. If the working substance is a gas what is the appearance (make a sketch) of its pressure-volume diagram? What is the general appearance (make a sketch) of the temperature-entropy diagram?

13. What factors affect the appearance of the pressure-volume diagram of the Carnot cycle when the working substance is a vapor? Draw several such diagrams and show the effects. What is the general appearance (make a sketch) of the temperature-entropy diagram?

14. State the formula which expresses the efficiency of the Carnot cycle and show its derivation.

15. How can the Carnot engine be made into a refrigerating machine? Describe its operation as a refrigerating machine and draw its pressure-volume and temperature-entropy diagrams.

16. State the formula which expresses the efficiency of the Carnot refrigerating machine and show its derivation.

17. What is the important relationship between heat-engine efficiency and the temperatures of the hot and cold bodies? Show the proof of the relationship.

18. Why is the *Rankine* cycle, rather than the Carnot cycle, taken as the standard for vapor heat engines?

19. Explain with a sketch the apparatus which is required to constitute a complete plant which is to operate on the Rankine cycle and trace the changes of the working substance in its passage through the cycle.

20. Draw the pressure-volume diagram of the theoretical Rankine cycle and correlate it with the apparatus described in answer to the preceding question.

21. Show that the area enclosed by the pressure-volume diagram of the Rankine cycle represents the net work of the cycle.

22. In general, what three forms (make sketches) may the temperature-entropy diagram of the Rankine cycle have? Assume steam conditions and plot, from values taken from Steam Table 394, the temperature-entropy diagram of a Rankine cycle.

23. Is the indicator diagram of a steam engine the same as the pressure-volume diagram of its cycle? Why?

24. Draw the theoretical indicator diagram of a Rankine-cycle engine without clearance. How does clearance affect the operation of the engine? Show the theoretical indicator diagram for an engine with clearance.

25. State the formula which expresses the efficiency of the theoretical Rankine-cycle engine. Show the derivation of this formula.

26. For given hot and cold bodies, which would have the greater efficiency—a Rankine-cycle engine or a Carnot-cycle engine?

27. Wherein does the theoretical steam-engine cycle differ from the theoretical Rankine cycle? Which of these two cycles is it more desirable to have a steam engine follow? Why?

28. Why does the actual steam-engine indicator diagram differ from the theoretical? Explain fully each of three principal losses

29. What is the difference in construction between a steam engine and an air engine? What is the difference between their theoretical indicator diagrams?

30. Is an air engine actually a heat engine? For what services are air engines used? What is their principal advantage?

31. What class of engine has replaced the air engine as a commercial heat engine?

32. In what class of engines is the *Otto* cycle used? Is the Otto cycle an efficient one? What cycle, used in engines of the same class, is more efficient?

33. Explain the operation of an engine employing the Otto cycle. Draw the theoretical pressure-volume diagram.

34. Write the formula for the efficiency of the theoretical Otto cycle. How is the formula derived?

35. In engines of what class is the *Diesel* cycle employed? To what fuels is it particularly adapted?

36. Explain the operation of an engine employing the Diesel cycle. Draw the pressure-volume diagram. What variations may the pressure-volume diagram have? Explain.

37. What is a *compressor?* In what kind of machines are compressors nearly always used? What is its pseudo cycle often called?

38. Explain the operation of a compressor without clearance, using pressure-volume diagram. In what respects is the operation different in a compressor with clearance?

39. Define *low-pressure capacity. Volumetric efficiency.*

40. Does the clearance volume of a compressor introduce any energy loss? Any capacity loss?

41. Which is generally more desirable—adiabatic or isothermal air-compression? Why? What kind of compression is usually obtained? Why?

42. Draw a sketch to show wherein the actual indicator diagram of a compressor differs from the theoretical.

43. What is a *compound* compressor? When are they generally used? What is the *intercooler?*

44. What are the objects of compounding compressors? Explain, using diagrams if necessary.

45. How would you determine the proper intercooler pressure for a compound compressor with ideal or perfect intercooling?

46. Explain, by the aid of a sketch, the cycle of the *air refrigerating machine.* When is a machine which employs this cycle called a *dense-air* machine?

47. Draw the pressure-volume diagrams of an air-refrigerating-machine cycle and correlate it with the required apparatus.

48. Draw the temperature-entropy diagram of an air-refrigerating-machine cycle and by its means show the several energy quantities.

49. What is the principal difference between the air and the vapor refrigerating-machine cycles? What advantage have the latter?

50. Draw a sketch and with it explain the operation of a vapor refrigerating machine. How does it compare with the air machine in number of pieces of apparatus?

51. Draw the typical pressure-volume and temperature-entropy diagrams of the vapor-refrigerating-machine cycle and correlate them with the apparatus used. Do the diagrams have exactly the same significance as do those for the other cycles which are herein discussed? Explain.

52. What is the meaning of the term *indicated work* as used in connection with heat engines and refrigerating machines? How is it measured?

53. On what kind of machines cannot the indicated work be measured? Why?

54. Draw a diagram to illustrate and with it explain the many ways in which losses occur in heat engines.

PROBLEMS ON DIVISION 12

1. A heat engine converts into work 68,000 B.t.u. per hr. whereas it is supplied with 200,000 B.t.u. per hr. What is its thermal efficiency?

2. A refrigerating machine abstracts 800,000 B.t.u. per hr. from a cold room and consumes 194,500,000 ft.-lb. of mechanical energy per hour. What is its coefficient of performance?

3. What would be the thermal efficiency of a Carnot engine whose hot and cold bodies have temperatures of 2,800 and 60° F. respectively?

4. What would be the coefficient of performance of a Carnot refrigerating machine with which an inside temperature of 0° F. was to be maintained while the outside temperature is 90° F.?

5. The inventor of a certain internal-combustion engine claims that the engine will produce 1 hp.-hr. with a consumption of only $\frac{1}{8}$ lb. of fuel which has a heating value of 18,000 B.t.u. per lb. It is found that the maximum temperature of the gases within the cylinder is 2,700° F. and that the gases are exhausted at a temperature of 850° F. Is the inventor's claim probable?

6. What is the efficiency of the Rankine cycle with steam leaving the boiler at 150 lb. per sq. in. abs. and 250° F. of superheat and leaving the engine at 1 lb. per sq. in. abs.?

7. How much work would be obtained from 1 lb. of steam in passing through the cycle of Prob. 6, and how many pounds would have to be circulated per indicated horsepower-hour?

8. The clearance space of a 6- by 15-in. Otto gas engine was found to hold 5 lb. of water. What is its theoretical thermal efficiency?

9. An air compressor has a displacement volume of 6 cu. ft. and a clearance of 5 per cent. If the compressor operates between 5 and 100 lb. per sq. in. gage, what is its volumetric efficiency? ($n = 1.3$).

10. An air compressor which has a displacement volume of 8 cu. ft. and a clearance of 4 per cent., operates adiabatically between 0 and 70 lb. per sq. in. gage. What volume of air does it take in per stroke?

11. What would be the proper intercooler pressure for a two-stage air compressor which draws in air at atmospheric pressure and discharges at 110 lb. per sq. in. gage? (Assume perfect intercooling.)

12. In a dense-air refrigerating machine, the pressures in the cooling coils and refrigerating coils are, respectively, 130 and 40 lb. per sq. in. gage. The air enters the compressor at 34° F. The air leaves the cooling coils at 70° F. Assuming adiabatic compression and expansion, find the coefficient of performance.

13. In the machine of Prob. 12, how many pounds of air would have to be circulated per hour and what power would have to be supplied if it is desired to extract 2,000 B.t.u. per hr. from the cold body?

14. If, in a plant similar to that of Fig. 387, it is desired to maintain a temperature of 30° F. in the room *R* and the water entering the condenser *B* is at the temperature of 70° F., what must be the pressure of the ammonia in coils *B* and *E*? (Assume that condensation takes place at 80° F. and vaporization takes place at 20° F.)

15. If the machine of Prob. 14 is to extract 2,000 B.t.u. per hour how many pounds of ammonia must be circulated per hour? (Liquid ammonia leaves *B* at 75° F. and the vapor leaving *E* is dry saturated.)

16. The indicated work of an engine is 11,220 ft.- lb. per revolution. The shaft output of the same engine is 9,537 ft.-lb. per revolution. What is the mechanical efficiency of the engine?

17. The indicated work of a compressor which requires 25 hp. at its shaft and operates at 200 r.p.m. is found to be 3,300 ft.-lb. per revolution. What is the mechanical efficiency of the compressor?

18. A steam engine on test was found to require 3,965 lb. of dry saturated steam per hour at 115.3 lb. per sq. in. gage. The back pressure on the engine was 0.3 lb per sq. in. gage. The atmospheric pressure was 14.7 lb. per sq. in. abs. The indicated horsepower of the engine was 130 and the power at the shaft (brake horsepower) was 120. Compute the ideal Carnot efficiency, the ideal Rankine efficiency, the cylinder efficiency, the actual thermal efficiency, the mechanical efficiency, and the overall efficiency of the engine.

DIVISION 13

FUELS

437. A Fuel may be considered as any material that liberates its internal chemical energy (Sec. 28) as heat in commercial quantities, or burns, when it is united with the oxygen of the air. A portion of the heat which is thus liberated in the boiler furnace, or in the cylinder of an internal-combustion engine, is transformed by the engine into useful work. Or, the heat may be utilized in building heating, for the comfort of man.

NOTE.—WHEN TWO SUBSTANCES REACT CHEMICALLY TO FORM ANOTHER SUBSTANCE, HEAT IS OFTEN LIBERATED.—But for certain other chemical reactions, the addition of heat is necessary to effect the reaction. The chemical process of combustion, and of how heat is liberated thereby, is explained in Sec. 157 and in Div. 14 on COMBUSTION.

NOTE.—MOST FUELS CONSIST OF PURE CARBON, OR OF CARBON AND CHEMICAL COMPOUNDS OF CARBON with oxygen, hydrogen, nitrogen, and sulphur.

438. The Subject Of "Fuel" Is A Very Important One, since it may be the determining factor in the selection of a boiler, or even of the type of power plant that should be used. This selection should depend upon the type and quantity of fuel which is available in the community, or upon the facility of transportation of the fuel from some other community.

NOTE.—BESIDES KNOWING WHAT FUELS ARE AVAILABLE, and what they will cost delivered to the plant, something should also be known about the classes of fuels, the substances contained in them, and the heat values of the fuels. Only a few of the more important facts concerning fuels can be treated herein.

439. There Are Three Classes Of Fuels, under which all may be grouped according to their state of matter (Sec. 49): (1) *Solid.* (2) *Liquid.* (3) *Gaseous.* Fuels of each of these three classes are available, either in their natural states or as they have been prepared by man. Fuels of the different classes are discussed in following sections.

440. Natural Solid Fuels exist in, among others, the forms listed below. There are many other natural solid fuels such as *corncobs* and *tanbark*. However, they are of relatively minor practical importance and hence will not be treated here.

The Straw Of Wheat, Rye, And Other Grains is sometimes used as fuel for the engines in the harvest fields. Boilers have been designed especially for burning them. They have never been used except where straw is very plentiful and other fuels scarce. Straw would not be purchased for this purpose, as it burns very rapidly and is inconvenient to handle.

Bagasse, which is sugar cane from which the juice has been pressed, is used in sugar-plantation mills where a large amount is available. It is cheap and makes a fair steaming fuel for the sugar mills.

Sawdust, Bark, Slabs, And Other Sawmill Refuse, found around a sawmill may be used to fire the furnaces of the mill. Its low heating-value renders it uneconomical as a fuel if it must be transported any considerable distance.

Wood is sometimes used as a fuel in the household and for steaming purposes. Its utility has been demonstrated for ages. However, due to the scarcity of lumber for building purposes, wood is being used less frequently as a fuel as time progresses.

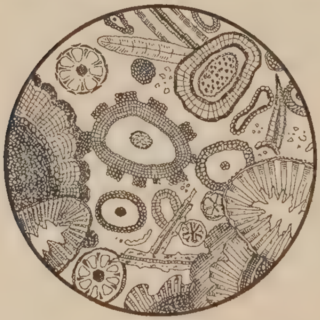


Fig. 391.—Microscopic enlargement of a minute fragment of coal.

Coal (Fig. 391) is by far the most important of the solid fuels. This is due to its abundance, ease with which it may be handled, and its heating-value. The fuels listed above are primarily of vegetable origin. Coal also is derived from the same source. Investigation shows that, many centuries ago, there were great forests of vegetation, much more abundant and dense than any which now exist. These forests thrived in climates considerably warmer and much more humid than those of the present day. Then, some geological upheaval occurred. Thereby these growths of vegetation were inundated with earth, rocks and water. Eventually they were subjected to high temperatures, due to the internal heat of the earth (Sec. 69), and to great pressures. Thus the coal (Fig. 392) was formed. In some localities, coal is found near the surface of the earth. In others, the veins are far underground. Due to different original constituencies, pressures, temperatures, and periods of confinement, the coal of the different grades was formed.

Peat is another fuel which is used to some extent in certain localities. It is a mixture of partially decayed vegetable deposits and water. It is found under water, or in marshy ground, called *peat bogs*. When the water is dried from the material, it burns freely liberating considerable intense heat. It is clean and convenient to handle. Peat is used only in the localities in which it is found.

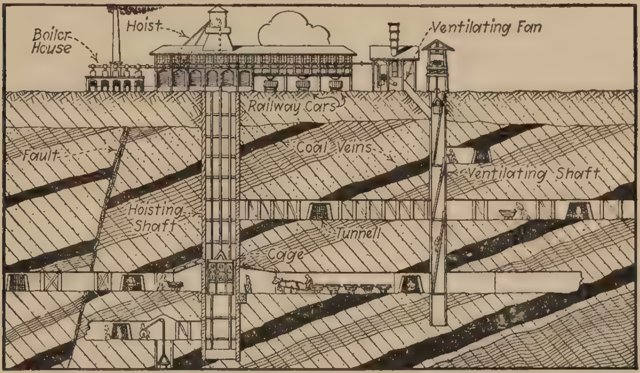


Fig. 392.—Section through an English colliery showing coal seams and method of working.

441. The Prepared Solid Fuels which are used extensively are charcoal and coke.

Charcoal is formed when the volatile matter (gases) which was originally contained in wood, is driven off without burning the wood. Charcoal is almost pure carbon. When it is burned under a strong draft, it produces an intense heat with practically no smoke. It is used in cupolas, furnaces, and in forges for special heating and heat-treating. The best grades of charcoal are obtained from beech, birch, and maple. Charcoal is a by-product from the manufacture of turpentine and wood alcohol.

Coke is formed when the volatile substances, which are contained in coal, are driven off without burning the coal. It, also, is nearly pure carbon. It is used for heating, especially in the metallurgical industries. It is seldom employed for power generation. Coke is a by-product from the manufacture of coal gas.

Note.—Briquetted Fuel is another of the solid fuels which is extensively used in European countries, and to some extent in the United States. The principal constituent of this fuel is, usually, coal which has been crushed and mixed with some combustible binding material, such as coal-tar pitch, and then pressed into briquettes. Fuel in this form has the advantage of being uniform in size and of making few clinkers. It gives off but little smoke, has a high heating value, and permits of a high rate of combustion. The expense of its preparation has, for most purposes, rendered its use uneconomical in America.

442. Petroleum Is The Most Important Of The Natural Liquid Fuels.—There is doubt as to the exact origin of petroleum. It is generally agreed, however, that it was formed by plant and animal matter, which was in prehistoric ages covered by earth and rocks. After being thus covered, the matter decayed. Then, for centuries it was subjected to confinement and pressure in porous rock and gravel, or in pockets below non-porous shales. This resulted in its being changed to the present liquid petroleum (Fig. 393).

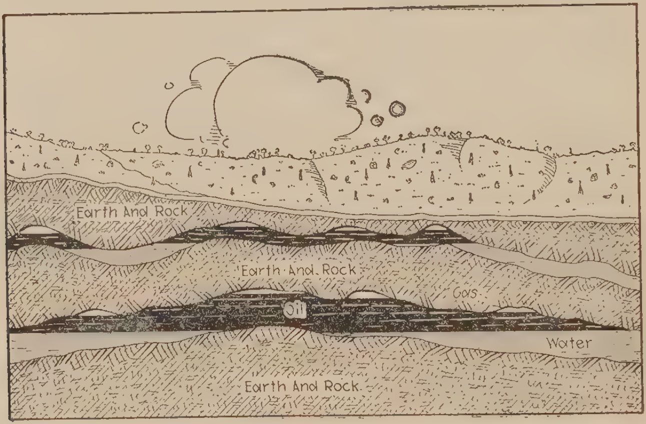


Fig. 393.—Illustrating the occurrence and mining of oil and natural gas.

443. Petroleum varies in color from light brown to dark brown, according to the locality from which it comes. The chief constituents of petroleum are hydrocarbons (chemical compounds of hydrogen and carbon). It is these hydrocarbons which render it valuable as a fuel. Petroleum and its products are used in boiler furnaces (Sec. 497) as a fuel for generating steam, or directly in explosion-engine cylinders (Sec. 531). The products from petroleum are also used for heating and lighting buildings. At present, petroleum is relatively plentiful. But, due to the continual increase in its use (Fig. 394) it is probable, that within the course of a relatively few years, the supply of liquid petroleum will be nearly exhausted. But even then, there remain the oil-shale deposits which will yield millions of barrels of oil; see note below.

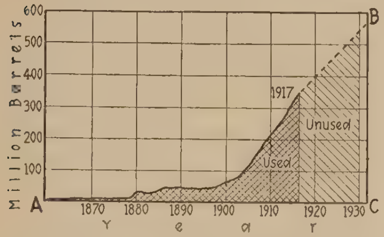


Fig. 394.—Graph showing the tendency of the United States to exhaust its reserve of unmined petroleum, shale oils not included. (The total area, *ABCA*, under the graph represents the original total petroleum supply of the United States. The double-hatched portion represents that used up to 1917. The single-hatched area represents the supply yet available on Jan. 1, 1918), Bulletin No. 102, Petroleum Smithsonian Institution.

Note.—Petroleum May Be Used As A Fuel In Oil-burning Boiler Furnaces And In Large Engines Of The Diesel Type, just as it is taken from the ground. Other substances such as road oils, benzene, paraffin wax, lubricating oils, are made (Fig. 395) from petroleum by fractional distillation (Sec. 444). At present there are only about 300 different products made from the crude petroleum. However, the ultimate possibilities in this respect appear to be unlimited.

Note.—There Is Another Source Of Oil Supply which is now being utilized to some extent. By heating and treating certain surface shales which are found in the Rocky Mountains, oil is derived. This will, doubtless, be the future source of our oil supply.

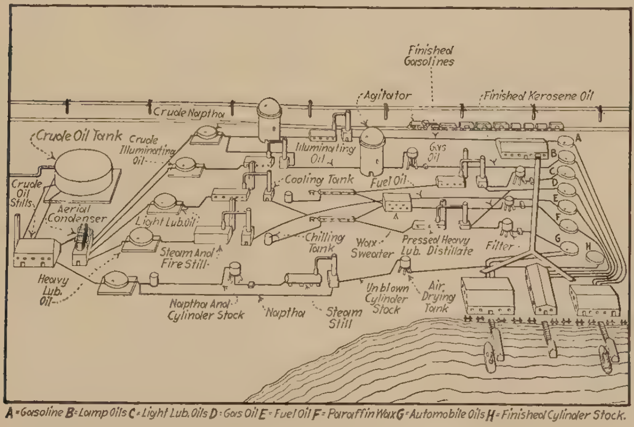


Fig. 395.—Diagram of an oil refinery.

444. Some Of The Prepared Liquid Fuels Are Obtained By Fractional Distillation Of Crude Petroleum as *gasoline*, *kerosene*, and *naptha*. There are many others. At different temperatures, different *distillates* vaporize from the crude petroleum (Sec. 443). Some are very volatile and have low specific gravities. For automobile and aeroplane engines (Fig. 396), gasoline is at present indispensable. Kerosene is used to a large extent in rural communities for lighting and heating. The *petroleum distillates* contain less impurities than the crude petroleum, are very rich in hydrocarbons, and constitute excellent fuels. Various grades of fuel oils, heavier and less volatile than kerosene and gasoline, are also distilled from crude oil. The heavier oils are distilled off at the higher temperatures and the lighter products at the lower temperatures, all as explained in Div. 10.

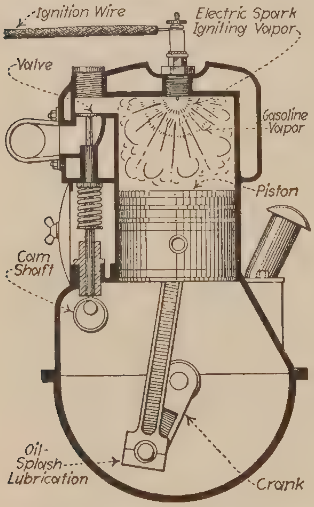


Fig. 396.—Vapor from the liquid fuel (gasoline), used directly in an internal-combustion engine.

445. Alcohol may be classed as a prepared liquid fuel. *Wood Alcohol* is obtained by the destructive distillation of wood. It finds its greatest use as a fuel for small stoves and heating-lamps in the laboratory and in other places where a clean effective liquid fuel is required. It is too expensive, however, for extensive use. *Denatured alcohol* is alcohol made by the distillation of a fermented solution of grain, molasses, syrups, or similar plant substances, to which has been added a small amount of wood alcohol or other poison. It is used for the same purposes as wood alcohol. Likewise, it is too expensive for extensive use.

Note.—Benzol is another liquid fuel. It is a by-product from the manufacture of coke. Because of the small quantities in which it is manufactured, it is not used to any great extent as a fuel at present. It is, however, a good fuel and may be used alone in internal-combustion engines, or it may be mixed with gasoline. In color and odor it resembles gasoline. Its freezing point is, however, rather high (about 40° F.).

446. A Gaseous Fuel Is The Theoretically Ideal Fuel.—As compared with the fuels of the other two states it is extremely easy to handle. Its combustion-rate may be readily regulated. It produces an even heat and, where it is used, there is no waste or inconvenience due to an ash residue.

Note.—Gaseous Fuels Contain Practically No Free Carbon, but have in them carbon compounds and uncombined gases such as oxygen, hydrogen, and nitrogen.

447. The Only Natural Gaseous Fuel Is "Natural Gas."—The origin of natural gas is similar to that of petroleum (Fig. 393). It is usually found adjacent to or above petroleum deposits. Also, it is sometimes found associated with coal deposits. The gas is, usually, found in pockets and under considerable natural pressure. It is obtained (Fig. 397) by drilling deep holes—wells—into the ground. Pipes are placed in the holes as the drilling progresses and the gas is then forced out through the pipes by its own pressures. Thence it is conveyed to the consumer by pipe lines.

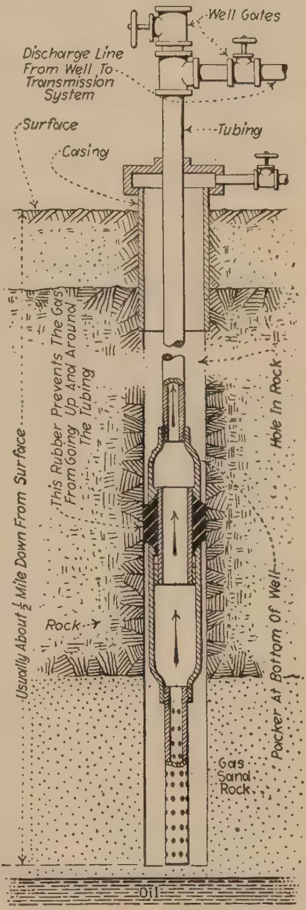

Well Gates
Discharge Line From Well To Transmission System
Surface
Tubing
Casing
This Rubber Prevents The Gas From Going Up And Around The Tubing
Usually About $\frac{1}{2}$ Mile Down From Surface
Hole In Rock
Rock
Packer At Bottom Of Well
Gas Sand Rock
Oil

Fig. 397.—Piping in a natural-gas well.

Note.—The Heating Value Of Natural Gas Varies Greatly.—The gases from some localities have a very high heating value, while those from others have a low heating value. Natural gas is a good fuel for use under boilers, and for heating, lighting, and cooking. In the immediate vicinity of the gas fields, the price is usually low. This may, in such communities, render it preferable to other fuels. Just as in the case of petroleum, however, the supply is being rapidly exhausted. Already, the demand for it far exceeds the supply.

448. Prepared Gaseous Fuels are derived from two main sources: (1) *Coal*. (2) *Oil*. In the operation of blast furnaces (coke, Sec. 441, ordinarily being used as the fuel) a large quantity of fuel gas is produced. It is called *blast-furnace gas*. Precautions are often taken to prevent the waste of the gas thus formed. It may then be utilized as fuel to generate steam in boilers or for direct utilization in internal-combustion engines. The quality of this gas is relatively poor. As it comes from the furnaces, the gas contains dust which must be filtered from it before the gas can be used in internal-combustion engines.

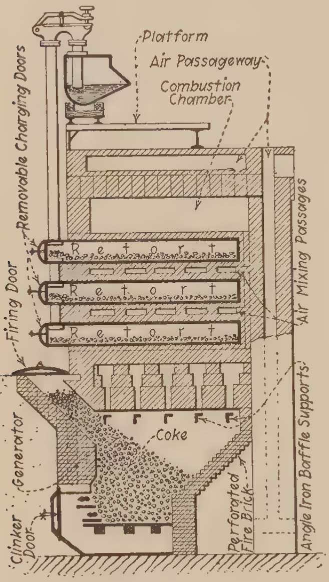


FIG. 398.—Section through a coal-gas retort.

449. Coal Gas is produced (Figs. 398 and 399) by heating bituminous coal in closed containers. It is manufactured in cities and sold for lighting and heating. The gas, which distills off from the heated coal, is stored in tanks or gasometers under pressure. From the gasometers it is piped to the consumer for use in stoves, gas-lights, water heaters, and other heat-consuming devices. It is generally too expensive to be

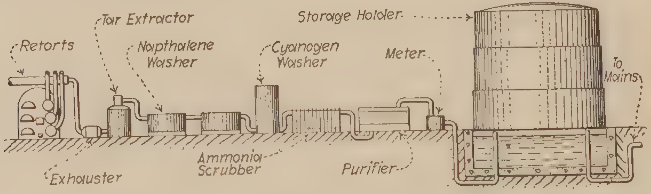


FIG. 399.—Illustrating the manufacture of coal gas.

used for generating steam for steam-power plant. The solid substance left after the gas has been expelled from the coal is *coke* (Sec. 441).

Note.—Other Gases Are Manufactured: *All oil-water gas* is obtained by atomizing crude oil and then mixing it with steam. *Pintsch gas* is manufactured by allowing oil to fall, drop by drop, on a heated surface. The gas thus formed is collected and compressed, often to the liquid state. After compression, it is forced into metal cylinders for shipment to the consumer. Its chief use is for lighting. *Water gas* is produced (Fig. 400) by passing water, in the form of steam, through carbon which is at a red heat. The gas given off has a low heating value and burns with a blue flame. However, if vaporized oil is mixed with this gas, a luminous flame, suitable for lighting, is produced by the combustion of the mixture in air. *Air gas* and *blast-furnace gas* are produced by passing a minimum quantity of air through a thick layer of glowing coke or other solid fuel—the resulting gas has a low heating value.

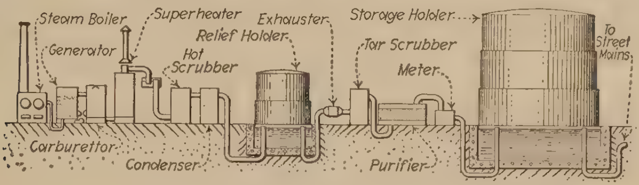


Fig. 400.—Illustrating the manufacture of water gas.

450. There Are Two Methods Of Determining The Chemical Energy In Fuels, Which Is Liberated As Heat Energy when combustion occurs and which may be partially utilized in doing useful work: (1) *By analysis.* (2) *By calorimeter tests.* If an *analysis* of a fuel is made (as hereinafter described) and its various constituents thereby determined, it is then possible, by applying certain graphs or formulas, to determine, with approximate accuracy, its *heating value in British thermal units per pound.* If a *calorimeter test* (described in a following section) is made on a fuel sample, the heating value of the fuel may thereby be determined almost exactly. It follows then, that the analyses may be employed for approximate determinations and the calorimeter tests for more exact determinations.

Note.—The Following Information Concerning Fuel Analyses And Tests, Relates Almost Entirely To Coal, but the same general process is followed for the determination of the available heat energy in a fuel of any class.

451. Table Of Heating Values And Constituents Of Fuels. The data shown in the table is only comparative as the heating values and composition of the fuels vary widely. The values here given are the average or usual ones.

	Fuel	Ultimate analysis						Proximate analysis				Heat value in B.t.u. per lb.		Authority*
		C	H_2	O_2	N_2	S	Ash	Moisture	Volatile	Fixed carbon	Ash	Higher	Lower	
Solid	Anthracite coal (Wilkesbarre, Pa.)	88.86	2.04	1.95	0.90	0.35	5.90	3.45	2.75	87.90	5.90	13,950	....	G
	Semi-anthracite coal (Coalhill, Ark.)	76.44	3.82	4.30	1.37	1.99	12.08	2.36	12.68	72.88	12.08	13,259	....	G
	Semi-bituminous coal (W. Virginia)	81.95	4.30	3.68	1.29	0.97	7.81	1.42	20.72	70.05	7.81	14,686	....	G
	Bituminous coal (Horsecreek, Ala.)	71.58	5.01	8.50	1.65	0.72	12.54	2.34	31.84	53.28	12.54	12,850	....	G
	Bituminous coal (Coffeen, Ill.)	54.59	5.49	21.52	1.11	4.01	13.28	14.43	29.48	42.81	13.28	10,064	....	G
	Sub-bituminous (Red Lodge, Mont.)	59.08	5.37	21.52	1.33	1.73	10.97	11.05	35.90	42.08	10.97	10,539	....	G
	Lignite (N. D.)	41.87	6.93	44.94	0.69	0.48	5.09	36.78	28.16	29.97	5.09	7,002	....	G
	Peat (Fla., Putnam Co.)	.....	.....	.....	....	....	.....	.....	52.80	38.29	8.91	9,423	....	P
	Coke, Connellsville	.....	.....	.....	....	0.90	.....	.....	0.93	87.43	11.64	12,600	....	M
	Charcoal	84.00	1.00	.....	....	....	3.00	12.00	10.00	.....	.....	12,850	....	M
	Wood, white oak	49.64	5.92	41.16	1.29	....	1.97	.....	.....	.....	.....	5,400	....	G
	Straw	36.06	5.04	37.97	0.42	....	4.75	15.75	.....	.....	.....	5,155	....	G
	Bagasse, dry	43–47	6.0	45–49	0 – 4	....	1.5–3.0	.....	.....	.....	.....	8,350	....	M
Liquid	Fuel oil crude (Col. Midway)	86.58	11.51	0.74	....	0.82	.....	.....	.....	.....	.....	18,613	....	G
	Gasoline, high grade	84.00	15.0	.....	1	....	.....	.....	.....	.....	.....	20,000	18,500	M
	Kerosene	84.5	15.5	.....	....	....	.....	.....	.....	.....	.....	21,500	....	M
	Alcohol, denatured	.....	.....	.....	....	....	.....	.....	.....	.....	.....	11,600	10,500	M
	Benzol	.....	.....	.....	....	....	.....	.....	.....	.....	.....	18,000	17,260	M
Gaseous												B.t.u. per cu. ft.		
	Natural gas (Osage Co., Okla.)	.....	.....	0.00	4.6	....	.....	.....	.....	.....	.....	1,004	....	M
	Coal gas (Harrisburg, Ill.)	.....	.....	0.8	6.0	....	.....	.....	.....	.....	.....	632	568	M
	Water gas	.....	.....	0.50	5.5	....	.....	.....	.....	.....	.....	295	....	M
	Producer gas	.....	.....	.....	....	....	.....	.....	.....	.....	.....	140–175	125–132	G
	Pintsch gas	.....	.....	2.0	3.0	....	.....	.....	.....	....	.....	1,500	....	M

* G—Gebhardt, "Steam Power Plant Engrg." M—Marks, "Mech. Engrs' Hb." P—Poole, "The Calorific Power of Fuels."

452. The Heating Value Of A Fuel may be defined as the number of heat units given up by it or liberated when a unit quantity of the fuel is completely burned (in oxygen or in the air). For solid and liquid fuels, heating values are generally expressed in British thermal units per pound of fuel. For gaseous fuels, heating values are generally expressed in British thermal units per cubic foot of the gas (measured at a standard pressure and temperature of 30-in. mercury column and 62° F.). Fuel is purchased primarily to produce heat. Therefore, the greater number of British thermal units that a given amount of the fuel will produce, the better is the fuel, other factors being equal.

Note.—The Heating Values Of Gaseous And Liquid Fuels Should Be Expressed As Either "Higher" Or "Lower" values, sometimes called *total values* and *net values*. When, in making heat-value determinations of fuels, the products of combustion are cooled below 212° F., any water vapor which might have been formed by the combustion of hydrogen in the fuel and which passes off as a product of combustion, is condensed. In condensing, the water vapor gives off its latent heat of vaporization. The "higher heating value" of a fuel includes this latent heat. The "lower heating value" does not include this latent heat. The heating values of solid fuels, as generally computed, are the "higher" heating values. The hydrogen of a solid fuel is thus generally neglected when its heating value is given. The reason for this is that it is extremely difficult to determine accurately the lower heating value of a solid fuel unless an ultimate analysis of the fuel is available. (See White, "Gas and Fuel Analysis," page 281.) Ultimate analyses of fuels are expensive and are seldom made.

However, it is a fact that the lower heating value provides a better index as to the effectiveness of a fuel, for the usual power plant conditions, than does the higher heating value. This is because, in the usual power plant, the combustion gases leave the steam-generating equipment at a temperature higher than 212° F. Thus, the water vapor which was formed by the hydrogen when the fuel was burned in the furnace has not condensed and given up its latent heat of evaporation to the flue gases if the gases leave the steam-generating equipment at a temperature higher than 212° F. Chemical- and bomb-type calorimeter determinations give (unless involved corrections are made) "higher" heating values—because with these calorimeters—the water vapor which is evolved in the crucible condenses and gives up its latent heat of vaporization to the jacket water in the calorimeter.

453. The Quality Of A Fuel May Be Determined By An Analysis.—There are two analyses in general use for coals:

(1) *Proximate analysis.* (2) *Ultimate analysis.* The proximate analysis is relatively simple and does not necessarily, require a chemist for its performance. The purpose of a proximate analysis is to determine the amount of the following substances which are contained in the fuel: (1) *Moisture.* (2) *Volatile matter.* (3) *Fixed carbon.* (4) *Ash.* The ultimate analysis must be made by a competent chemist. This chemical analysis shows the amount, of the following substances in the fuel: (1) *Moisture.* (2) *Carbon.* (3) *Hydrogen.* (4) *Oxygen.* (5) *Nitrogen.* (6) *Sulphur.* (7) *Ash.* In each of these analyses, the amount of each substance contained in the fuel is usually expressed as a percentage by weight of the whole.

NOTE.—IF THE POWER-PLANT MAN IS TO INTELLIGENTLY PURCHASE FUEL, he should know which of these constituents tend to make a good or a poor fuel for the purpose for which it is to be used. Either of the above analyses will provide him with valuable information.

454. The Proximate Analysis Of A Coal provides data whereby the behavior of the coal in a furnace may be intelligently predicted. Before making the analysis, however, great care must be taken to insure that the coal which is being tested is a really *representative sample* of the coal from which it is taken. The following notes on the sampling and analysis of coal are abstracted from POWER PLANT TESTING by J. A. Moyer.

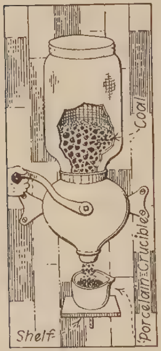


FIG. 401.—Coffee-mill used for grinding the coal sample prior to pulverizing.

SAMPLING.—For all tests in which an analysis of the coal or its calorific value is to be determined, it is very necessary that the sample to be tested be selected with the greatest care. Proportionate amounts should be taken of both large and small sizes as well as of the dust. At least 200 lb. of coal is collected for the process of sampling for the analysis. This amount of coal is to be broken up on a clean floor by any convenient means to a size of about ½-in. diameter, then thoroughly mixed and spread out on a flat circular pile. This pile is then "quartered" and the opposite quarters are discarded. The remainder is now broken up to about ¼-in. diameter pieces and the mixing, quartering and discarding is continued until from 5 to 10 lb. remains. This is to be put into a glass jar or a tin can that can be made airtight. The sealing should be carefully done, to prevent any deterioration of the sample in transportation to the laboratory where the analysis is to be made.

In the laboratory the coal should be emptied from the jar or can and crushed (a coffee mill, Fig. 401 may be used) to a fineness of about a 20-mesh sieve (20 meshes to the inch). The coarser pieces may be broken in a mortar (Fig. 402). The crushed coal is thoroughly mixed and a small portion which is to be used for the analysis—about 2 or 3 oz.—is put into an airtight bottle. The remainder of the crushed coal is put back into the jar or can and sealed. It is to be retained for possible future use for check tests.

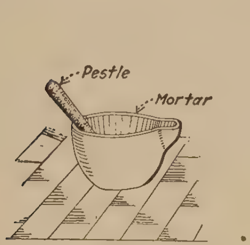


Fig. 402.—Mortar and pestle for pulverizing coal sample.

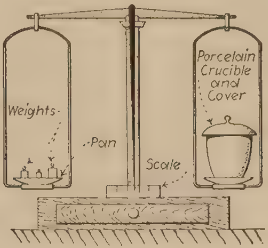


Fig. 403.—Weighing coal sample.

Moisture.—Weigh into a covered crucible about 4 grams (about ⅛ oz.) of the coal which passed through a 20-mesh sieve, that was prepared and bottled for analysis as described above (Fig. 403). This should be done as quickly as possible to avoid loss of moisture to the air. Remove the crucible cover and heat in an oven or similar receptacle (Fig. 404) for 1 hr. at a temperature of from 220° to 230° F. At the end of the hour, replace the cover on the crucible, remove it from the oven and place it in a *desiccator* (Fig. 405) to cool. When the crucible and the coal which it contains have cooled to nearly the room temperature, they should be weighed. Again remove the crucible cover and heat as before in the oven for ½ hr. longer. If the weight has remained constant, no more heating is necessary. The difference between the first and last weighings is the moisture in the coal.

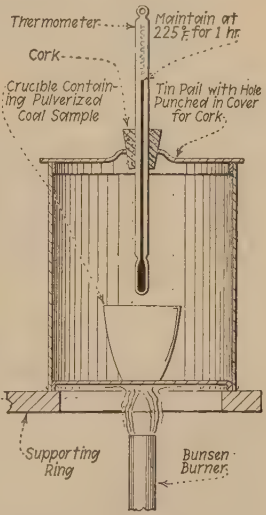

Thermometer
Maintain at 225°F. for 1 hr.
Cork
Crucible Containing Pulverized Coal Sample
Tin Pail with Hole Punched in Cover for Cork
Supporting Ring
Bunsen Burner

Fig. 404.—Drying the coal sample for "moisture" determination.

Volatile Matter.—Now weigh out a new sample of about 1 gram (1/30 oz.) of the "20-mesh" crushed coal into a platinum (or platinum substitute) crucible weighing 20 to 30 grams (⅔ to 1 oz.) and having a closely fitting cover. Support the covered crucible on a chemist's triangle (Fig. 406) of nichrome steel or of platinum which should be 3 to 3½ in. above the top of a good Bunsen burner. (The burner should give a free flame about 8 in. long.) Heat the covered crucible for 7 min. in the full flame of the burner. Cool the crucible in a desiccator and then weigh carefully. The loss in weight is the sum of the volatile plus the moisture. The room in which the test for volatile matter is made should be free from drafts which might cause a variation in the intensity of the flame.

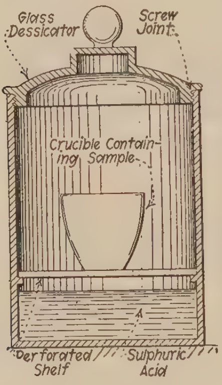


Fig. 405.

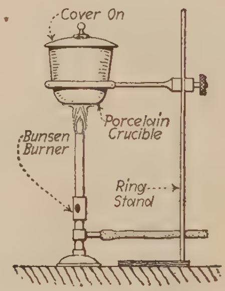


Fig. 406.

Fig. 405.—Desiccator to prevent sample from absorbing moisture while cooling. The desiccator utilizes the fact that certain substances (sulphuric acid in the one shown here) have a great affinity for water and will absorb water vapor from surrounding air. Sulphuric acid absorbs water vapor much more rapidly than does dry coal. Hence, when a dry coal sample—which also tends to absorb vapor from the air—is placed in a desiccator to cool, the moisture inside the desiccator is quickly absorbed by its air-drying substance. Therefore, the coal sample is prevented from absorbing moisture while cooling.

Fig. 406.—Heating crucible containing coal sample for "volatile" determination.

Fixed Carbon And Ash.—Remove the cover from the crucible which was used in the "volatile" test and heat the crucible and the residue with a Bunsen flame or with an air-blast lamp until all of the carbon has been burned, and the weight of the crucible and contents becomes constant. The contents of the crucible may be stirred slightly with a platinum wire to break up the ash—which should become a powdery mass when combustion is complete. Combustion is assisted by inclining the crucible on the triangle during this test so as to admit air more freely for oxidation. After cooling in a dessicator, make a final weighing of the crucible and contents. The difference between this weight and the weight of the empty crucible, without its cover, is the weight of the ash. The weight of the fixed carbon is determined by subtracting the sum of the weights of the moisture, volatile, and ash from the original weight of the sample of coal tested.

Note.—Weighings Should Be Made With Chemical Scales which are sensitive to $\frac{1}{1,000}$ of the amount weighed. Two determinations of the complete analysis should be made of each sample and the results should check within ½ per cent. of the weight of the coal used.

The Percentage Of Each Of The Different Constituents May Now Be Computed.—From these percentages the value of the coal may be intelligently judged. If the ash content is high, it may be assumed that the coal is a relatively poor one. A large percentage of ash in a coal lowers its heating value, causes trouble with clinkers, and increases the expense of removing ashes. The amount of volatile indicates whether the coal will burn with a long flame or a short flame and whether it will tend to produce smoke. The greater the amount of volatile contained in the coal, the longer will be the flame and the more likely will be the production of smoke. Whether or not the fuel burns with a long or a short flame will determine the method of firing which should be used. to may also be a determining factor in the selection of the proper type of ~~If~~ furnace.

Combustible is the term applied to that portion of the coal which is not included in the ash and the moisture content. That is: The *combustible* = (*volatile*) + (*fixed carbon*). In general, the larger the percentage of fixed carbon and volatile, the higher will be the heating value of the fuel.

Note.—Occasionally Coal May Loose A Part Of Its Moisture By Air Drying, or other means. If a proximate analysis which was made upon a sample of the dried coal is used instead of upon a sample of the undried coal, the results obtained thereby might be erroneous. Therefore, the proper method of procedure is to make the proximate analysis on the basis of "*As Received.*" Then, by the method given in the following example, reduce the analysis as made on this basis, to that of the *Dry Coal* basis.

Example.—Suppose the proximate analysis of a sample of coal, made on the "*As Received*" basis, shows that it contains the given percentages by weight of the following substances: *moisture*, 8.50; *volatile*, 37.75; *fixed carbon*, 51.10; *ash*, 2.65. What would be the percentages on a *Dry Coal* basis? Solution.—The *content of the coal*, omitting the moisture, is $100 - 8.50 = 91.50$ *per cent.* Then, the percentage of *volatile* in the sample on the *Dry Coal* basis $= 37.75 \div 91.50 = 41.25$ per cent.; *fixed carbon* $= 51.10 \div 91.50 = 55.90$ *per cent.; ash* $= 2.65 \div 91.50 = 2.85$ *per cent.*

Example.—If the ash be eliminated from the analysis on the *Dry Coal* basis, what per cent. of the *combustible* is the volatile? What per cent. is the fixed carbon? Solution.—From the above solution: (*The per cent. of volatile*) + (*the per cent. of fixed carbon*) $= (41.25 + 55.90) = 97.15$ *per cent. combustible.* Therefore the combustible contains: $(41.25 \div 97.15) = 42.48$ *per cent. volatile*, and $(55.90 \div 97.15) = 57.52$ *per cent. fixed carbon.*

NOTE.—FIG. 407 SHOWS GRAPHICALLY THE APPROXIMATE HEATING VALUES in B.t.u. per lb. of coal that may be expected in coals of various *ratios of volatile to fixed carbon in the combustible.*

EXAMPLE.—What is the approximate heating value in B.t.u. per pound of the above coal? SOLUTION.—The *ratio of volatile to fixed carbon* = (42.48 ÷ 57.52) = 0.735. From Fig. 407, 1 *lb. of this coal contains* 14,400 *B.t.u. per lb. of combustible.* From the above example, the "*Dry Coal*" *sample contains* (55.90 + 41.25) = 97.15 *per cent. combustible.* Therefore, the *heat value of* 1 *lb. of the* "*Dry Coal*" = (97.15 × 14,400) ÷ 100 = 13,990 *B.t.u.*

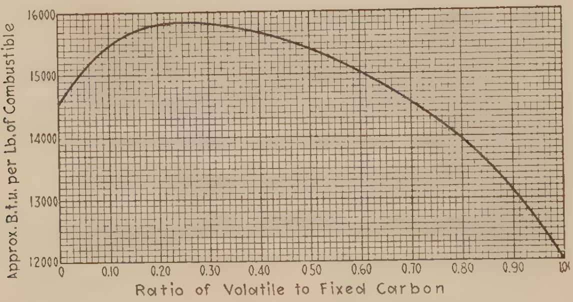


FIG. 407.—Graph showing the approximate heating value of coal per pound of combustible.

455. The Ultimate Analysis Of A Coal is made for the purpose of determining the percentage, by weight, of the elementary constituents or elements contained therein. This chemical analysis determines the percentages of, *carbon*, *hydrogen*, *oxygen*, *nitrogen*, and *sulphur* contained in the sample. The analysis method which is employed is complicated and necessitates skillful manipulation. Therefore the analysis must be made by a competent chemist. The process of making such an analysis will not be described herein. In performing this analysis, the chemist may also determine the amounts of *ash* and *moisture* in the coal and also the elements which constitute the ash. An ultimate analysis having been made, the heating value of the coal may be determined approximately by substituting in For. (326), Sec. 469.

NOTE.—FOR THE REASONS GIVEN UNDER PROXIMATE ANALYSIS (Sec. 454) the basis—whether "Dry" or "As Received"—should be known so that correct comparisons may be made between the analyses of samples of different coals.

456. Fuel Calorimeters Are Devices For Measuring The British Thermal Units Heating Values Of Fuels. (See Sec. 452.) Both coal (Fig. 408), and gas calorimeters of several different types are manufactured. The majority of the instruments of these various types operate on the same principle. They measure the heat, usually in B.t.u., which is liberated, by the combustion in oxygen, of a given weight of the fuel which is under test. In them, the heat which is liberated by the combustion of the test-sample is permitted to pass into a known weight of water. Then the rise in temperature of the known weight of water is noted. The calorimeters of the various types differ from each other principally in the method whereby the oxygen necessary for the combustion of the fuel is supplied. In some calorimeters, the combustion is effected by the oxygen in atmospheric air. In others almost pure oxygen gas is forced into the combustion chamber under high pressure. In still other types, the oxygen is supplied by some oxidizing agent—a powdered chemical—which is introduced into the combustion chamber of the calorimeter.

457. The Accuracy Of A Fuel Calorimeter depends upon two factors: (1) *The completeness of the combustion.* (2) *The amount of heat lost.* Various mechanical arrangements have been devised, whereby inaccuracy due to these factors has been reduced to a minimum.

Explanation.—Inexpensive coal calorimeters are frequently constructed according to the principle of that shown in Fig. 408. This is known as the *chemical type.* The steel crucible, *C*, is lined with some substance which is not affected materially by the products of combustion. This lining material is sometimes an enamel. In the more expensive types, the lining is of platinum or gold. While the test is being made, the crucible is immersed in the water, *W*, as shown. The water container, *A*, is enclosed by an air-jacket casing, to minimize the heat loss by radiation and conduction. The metal stem, *M*, is hollow and closed at the top by a screw-cap valve, *V*. Wires for the electric exploding-circuit pass through *M*. A fuse-wire, *P*, (usually iron) located in the crucible is connected in series with the two current-supply wires. To burn or explode the coal, which is under test, this fuse wire is heated to incandescence by an electric current. The wooden cover, *T*, fits tightly.

To load the crucible, it is removed and unscrewed from the crucible-cover. The sample of coal, after having been carefully dried, weighed, and thoroughly mixed with some powdered oxidizing chemical, (usually sodium peroxide), is placed in the crucible. The function of the chemical is to supply the oxygen necessary for the combustion. A quantity of water, *W*, sufficient to cover the crucible is now carefully weighed, and then poured into the water-container. The water is then stirred, with the stirrer, *S*, until the temperature becomes constant. The mixture is then ignited by closing the electric circuit. Rapid and complete combustion ensues. The heat liberated thereby is imparted to the water, thus raising its temperature. Since the thermometer is graduated to read in small fractions of a degree, the rise in temperature may be accurately determined. By the method explained in Sec. 454, the heat liberated by the combustion of the sample is now computed. Then, (*Number Of British Thermal Units Thus Obtained*) ÷ (*Weight Of The Coal Sample, In Pounds* = *Heating Value Of The Coal, In B.t.u. Per Pound.*

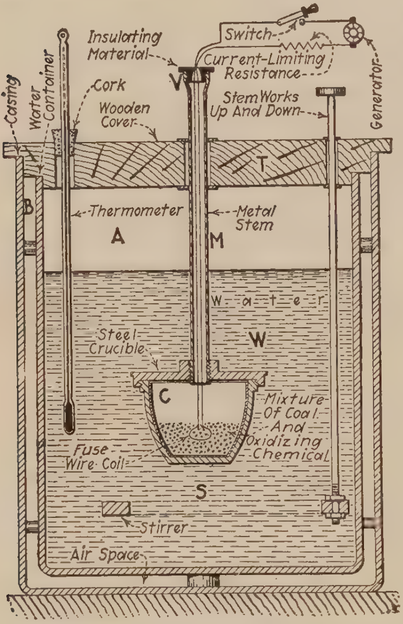


FIG. 408.—Construction of an inexpensive coal calorimeter.

NOTE.—IN BOMB-TYPE CALORIMETERS, which are the more expensive, commercially-pure oxygen gas is forced into the crucible, *C*, to provide for complete combustion of the coal. The gaseous oxygen is employed, instead of sodium peroxide or similar oxidizing agents.

NOTE.—ANOTHER METHOD OF DETERMINING THE HEATING VALUE OF COAL which is based an the amount of lead which a fuel will reduce from lead oxide, is as follows: A sample of about 1 gram (approximately 0.035,3 oz.) of the coal to be tested is dried and crushed to a fine powder. It is then intimately mixed with 60 grams of litharge and 10 grams of ground glass. This mixture is now placed in a clay crucible and covered with a layer of salt. The cover is put on the crucible. It is then heated olathe hottest part of a boiler furnace for about twenty minutes. After the crucible has cooled, the lead button is removed and carefully cleansed of the adhering slag. The lead is then accurately weighed. The B.t.u. per pound of coal may then be computed by the following formula:

(319) $$\mathbf{H} = 483\,\frac{\mathbf{W}_L}{\mathbf{W}_C}$$ (B.t.u.)

Wherein: **H** = heat value of the coal, in B.t.u. per pound. W_L = weight of the lead button, in grams. W_C = weight of coal sample, in grams. If this determination is carefully made, the results obtained thereby will usually be about 3 per cent. higher than those obtained from a similar sample of coal when tested with a bomb-type calorimeter.

458. Coal Is Classified Into Different Grades And According To Its Qualities And Constituents (see Table 451). Many classifications of coal have been made wherein different properties were made the basis of the classifications. The most common classification, however, is as follows: (1) *Anthracite.* (2) *Semi-anthracite.* (3) *Semi-bituminous.* (4) *Bituminous.* (5) *Sub-bituminous.* (6) *Lignite.*

Anthracite is the best of all coals for steaming purposes. It is practically all carbon. It is relatively clean and is difficult to ignite. It burns slowly with little smoke. Due to the fact that it is very hard it is frequently called *hard coal.* It has a high heating value, often liberating over 14,000 B.t.u. per lb. when burned in air. Since it contains a very small percentage of volatile, little flame results from its combustion. It is furnished by the trade in several sizes (Fig. 409).

Semi-anthracite burns more rapidly than does anthracite coal. It burns with a relatively short flame, but with a longer flame than that produced by anthracite. This is because the percentage of volatile is higher in the semi-anthracite. It produces but few clinkers and little smoke. It is also sometimes designated as *hard coal.*

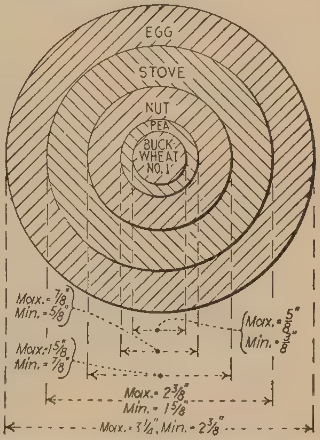


Fig. 409.—Actual sizes and names of some trade sizes of anthracite coal.

Semi-bituminous coal has an appearance similar to that of the anthracites. It has a very high heating value, contains little moisture and ash, and burns with but little smoke. It is somewhat softer than the so-called *hard coals.* It is excellent for steaming purposes, but due to the limited supply only small quantities of it are used.

Bituminous coals are, in America, by far the most common. Due to variations in the percentages of volatile matter, some of the bituminous coals burn freely with a short flame while others burn with a longer flame. It is difficult to burn them without considerable smoke. Large clinkers are usually formed. This grade of coal is well adapted for gas-making and is used extensively for that purpose. In the middle-western portion of America, it is the standard steam-power-plant coal. The heat value of the bituminous coals varies from below 10,000 to over 14,000 B.t.u. per pound.

Sub-bituminous coal does not differ greatly from the bituminous. However, it has a lower heating value and slacks more readily, when exposed to weather, than do the bituminous coals.

Lignite is the lowest grade of coal. It has a brown color. The heating value is low; it contains considerable moisture. It crumbles badly when dried and, due to its rapid deterioration, is difficult to transport. It is used only when other coals in the locality where it is found are very expensive. When made into briquettes, lignite makes a fairly good fuel.

459. Peat Is Not Generally Classed As Coal.—It is very wet when found and must be dried before it can be burned. It is a poor fuel and is used only when other fuels are too expensive.

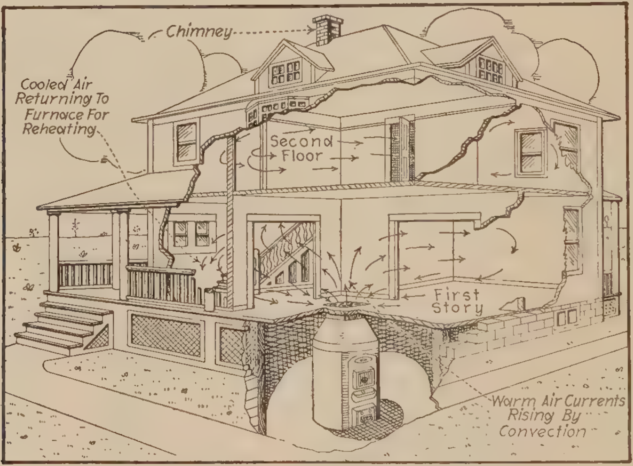

Chimney
Cooled Air Returning To Furnace For Reheating
Second Floor
First Story
Warm Air Currents Rising By Convection

Fig. 410.—Pipeless warm-air furnace burning coal heats house.

As shown in Table 451, the moisture content and the volatile matter are very high. However, most peats have lower B.t.u. values than that tabulated. Like lignite, if it is made into briquettes, a fairly good fuel results.

460. The Selection Of A Proper Fuel is an important economic problem. In selecting fuels for domestic uses (Fig. 410), the problem is not of great importance because the expenditures involved are relatively small. But, if a large building is to be heated, the selection of a proper fuel is of more consequence. An error will affect the fuel bill materially. For the power plant, the problem is a still more formidable one. For this service, an error in the selection may mean an annual loss of thousands of dollars.

NOTE.—THERE MAY BE SEVERAL GRADES OF COAL, OIL, OR GAS AVAILABLE for the operation of a fuel-consuming device. Hence a decision must be made as to which to use. The factors which should be considered are many. A few are: (1) *The kind, or kinds, of fuel available* in the locality. (2) *The comparative cost* between the various fuels available. (3) *The heat value* of the different fuels and their grades. (4) *The cost of handling.* (5) *Constancy of supply.* (6) *Equipment and capital* necessary for installing the equipment. (7) *Depreciation.* (8) *Cleanliness.* (9) *The nature of the load* on the plant (load factor). That is, the load at certain periods may be greater than the maximum rate of combustion obtainable from a certain fuel. It is not within the scope of this book to consider such problems in detail. Each individual problem may involve different treatment.

QUESTIONS ON DIVISION 13

1. What is fuel?

2. Into what three general classes may fuels be divided?

3. Why are straw, bagasse, sawmill refuse, etc., used for fuels?

4. Is wood used for steaming purposes to any great extent at the present time? Explain.

5. What are the factors that make coal an important fuel?

6. How was coal formed?

7. What is meant by a *prepared fuel?*

8. How is charcoal made? For what purposes is it most generally used?

9. What is the main constituent of coke? How is it made?

10. What is the source of crude petroleum?

11. Name the chief products of petroleum which are used as fuels.

12. What process is generally used in preparing fuel oils from the crude petroleum?

13. Why is not alcohol used more extensively as a fuel?

14. From what source is benzol derived? Benzine?

15. How is natural gas obtained from the earth?

16. Is gas a desirable fuel? Why?

17. Name and describe the method of manufacture of three prepared gaseous fuels

18. How may the quality of a fuel be judged?

19. What are the chief elements contained in coal?

20. What is understood by the meaning of the term heat content? Explain.

21. What two methods of making fuel analyses are in general use?

22. Describe briefly the method of making a proximate analysis?

23. What is meant by *dry coal? As received?*

24. If a coal analysis shows it to have a high ash-content, what is the usual conclusion concerning the quality of the fuel?

25. What are the usual burning characteristics of a coal having a high percentage of volatile matter?

26. What are the elements determined by an *ultimate analysis?*

27. Should an ultimate analysis be made on the coal while it is wet, or should it be dry? Give reasons for your answer.

28. Give the most common classification of coals.

29. Specify the characteristics of each class of coal.

30. What can be said of peat as a fuel?

PROBLEMS ON DIVISION 13

1. From the proximate analysis of a sample of coal, the contents were found to be: moisture, 12.50 per cent.; volatile 25.00 per cent ; fixed carbon, 57.35 per cent.; ash, 5.15 per cent. If the moisture is to be eliminated from the analysis, what will be the percentages of the other constituents? If the ash is eliminated from the analysis also, what percentage of the combustible is fixed carbon, and what percentage volatile?

2. What is the approximate heating value of the coal given in Prob. 1 in B.t.u per pound?

3. Two coals are available, each at $4.00 per ton. The percentages of the various constituents of one coal, as shown by a proximate analysis, are: moisture, 8.0; volatile, 16.0; fixed carbon, 64.0; ash, 12.00. The contents of the second by percentages were found to be: moisture, 6.0; volatile, 40.0; fixed carbon, 50.00; ash, 4.0. Which coal would be the more economical for the power plant to purchase? (Neglect all factors except the heating value).

4. What factors might cause the power plant manager to select the coal represented in Prob. 3 by the sample having the lower heating value?

DIVISION 14

COMBUSTION

461. Combustion May Be Defined as the process of the chemical union of a fuel *with oxygen* at a rapid rate, whereby light is evolved and an appreciable quantity of heat energy is liberated. In ordinary parlance, *combustion is burning.* By "liberated" is here meant the transformation of the internal chemical energy (Sec. 28) of the fuel and of the oxygen into heat energy. In Sec. 157 it is explained how heat is usually liberated when a chemical process occurs. The fuels which are ordinarily used for combustion and their constitutent elements are described in Div. 14. Combustion is what occurs when a fuel is burnt in a power-plant boiler furnace (Sec. 497). Now, most of the preventable losses in steam power plants occur in connection with the boiler and furnace (Sec. 499). A knowledge of combustion will enable one to minimize these losses. Hence, an understanding of combustion is essential to the successful operation of steam power plants.

462. Before Combustion Can Occur, The Temperature Of The Fuel Must Be Raised To The "Ignition" Or "Kindling" Temperature. The ignition temperature is that temperature at which the heat which is liberated by the union of the fuel with oxygen is evolved faster than it is conducted away. Then the fuel becomes hotter, the union proceeds more rapidly and this in turn heats the fuel and the immediate surroundings faster, until incandescence (flames) occurs. Oxidization—the slow union of the oxygen with a substance—may occur at any temperature. But combustion—the rapid union of oxygen with a substance—cannot occur below the ignition temperature. After the ignition temperature has once been attained (the fire "kindled" or "started") by a small portion of the fuel, the combustion will then proceed automatically. The heat released by the combustion of one small portion of the substance will heat other portions and so on until the entire mass is burning.

Note.—The Ignition Temperature For A Given Substance Is Not A Fixed Temperature but depends on a number of factors such as: (1) *The surface exposed by the consumed substance.* (2) *The pressure of the gas or vapor.* (3) *The presence or absence of adjacent substances.* (4) *The nature of the adjacent substances.* Hence no definite ignition temperature can be given for a substance unless other factors are specified also. Ignition conditions are determined by several variables of which the temperature is only one. For the usual conditions in boiler furnaces, ignition temperatures are approximately: Bituminous coal, 766° F. Semi-bituminous coal, 870° F. Anthracite coal 925° F.

463. The Principal Constitutents Of A Fuel Which Unite With Oxygen To Produce Combustion (Sec. 437) are: (1) *Carbon.* (2) *Hydrogen.* (3) *Sulphur.* When a substance is burned—when combustion occurs—its union with oxygen forms a third substance which is called the *product of combustion.* The weight of this product of combustion is exactly equal to the sum of the weights of the substances which united to form it. Furthermore, when two given substances combine to form a given product of combustion, they always combine in definite proportions by weight, and a definite amount of heat energy is liberated by the combustion. The amount of heat energy which is thus liberated by the combustion of the two given substances depends upon the weight of the two substances which have combined. *The heat of combustion or calorific value* of a fuel, as the terms are used in American boiler practice, is the heat, expressed in British thermal units, liberated by the complete combustion or oxidation of 1 lb. of the fuel in question.

Note.—The Principal Substances Which Are Contained In Coal (Sec. 453) are carbon, hydrogen, oxygen, nitrogen, sulphur, moisture or water, and ash. However, as stated above, practically the only constituents of coal which will unite with oxygen during the process of combustion are carbon, hydrogen, and sulphur. The oxygen, nitrogen, moisture, and ash will not combine with oxygen during the combustion. Furthermore, the carbon, hydrogen, and sulphur usually exist in the coal in such a condition that not all of them will combine with oxygen during combustion. However, the quantities of these substances which will not combine are so small that they may, in practice, be neglected without any appreciable error.

464. The Oxygen Which Is Necessary For Combustion Is Usually Obtained From The Air.—Thus, in a coal-burning furnace the oxygen for combustion is supplied by the air which is forced through the furnace by the draft pressure. Atmospheric air is a mechanical mixture of oxygen, nitrogen, and other gases. Since the nitrogen and other gases are incombustible they will hereinafter be considered as jointly being one gas and will be referred to as "nitrogen."

NOTE.—BY WEIGHT, AIR CONTAINS 23 PER CENT. OF OXYGEN AND 77 PER CENT. OF NITROGEN. Hence, 100 lb. of air would contain 23 lb. of oxygen and 77 lb. of nitrogen. Thus, if 23 lb. of oxygen is required for the combustion of a certain amount of coal, 100 lb. of air must be supplied to the furnace. Or, if 1 lb. of oxygen is required, 100 ÷ 23 = 4.35 *lb.* of air will be necessary to supply it. By volume, air contains approximately 21 per cent. of oxygen and 79 per cent. of nitrogen.

NOTE.—COMPLETE COMBUSTION is a combustion in which the combustible elements and compounds have united with all of the oxygen with which they are capable of entering into combination.

465. The Complete Combustion Or Burning Of Carbon results in a product of combustion called carbon dioxide and the liberation of heat; see Sec. 157. That is, in the complete combustion of carbon in oxygen, the carbon (C) and the oxygen (O_2) unite and form carbon dioxide (CO_2). The chemical formula which expresses this reaction is:

$$C + O_2 = CO_2 \tag{320}$$

$$12 + 32 = 44 \tag{321}$$

Beneath the chemical symbols in the above formula are written the *combining weights* of the substances. That is, in the complete combustion of carbon, 12 lb. of carbon combines with 32 lb. of oxygen and forms 44 lb. of carbon dioxide. Or, by simple proportion, it is evident that 1 lb. of carbon combines with 2.67 lb. of oxygen and forms 3.67 lb. of carbon dioxide. If measured at the same temperature and pressure, the volume of the carbon dioxide (CO_2) which is formed is exactly equal to the volume of the oxygen (O_2) from which it was formed. That is, if 100 cu. ft. of air was used to obtain the necessary amount of oxygen for the complete combustion of a certain amount of carbon, the products of combustion would be nitrogen and carbon dioxide (CO_2). If measured at the same temperature and pressure as the 100 cu. ft. of air, there would be 21 cu. ft. of carbon dioxide (21 per cent.) and 79 cu. ft. of nitrogen (79 per cent). Compare these values with that of air (Sec. 464). The quantity of heat energy which is produced in the complete combustion of 1 lb. of carbon is about 14,650 B.t.u. or the thermochemical equation for this reaction (Sec. 158) is:

$$(322)\quad 1\ lb.\ C + 2.67\ lb.\ O_2 = 3.67\ lb.\ CO_2 + 14{,}650\ B.t.u.$$

If the oxygen for combustion is obtained from the air (Sec. 464), the weight of air which will be required for the complete burning of 1 lb. of carbon (C) to carbon dioxide (CO_2) is $4.35 \times 2.67 = 11.61$ lb.

NOTE.—THE BURNING OF ANY COMBUSTIBLE obeys the same general laws as does carbon. However, the product of combustion, the weight which will combine with a given weight of oxygen, the volume of the product of combustion, and the heat energy liberated, depends upon the combustible and upon the product of combustion. These various properties for the principal combustibles which occur in coal are tabulated in Table 467.

466. Incomplete Combustion Of The Carbon Which Is In The Coal results in a waste of heat energy. Assume that 1 lb. of carbon undergoes incomplete combustion. That is, instead of its being burned to carbon dioxide (CO_2) it is only burned to carbon monoxide CO. From Table 467, it is seen that the burning of 1 lb. of carbon to carbon monoxide releases 4,430 B.t.u. whereas if it had been burned to carbon dioxide 14,650 B.t.u. would have been liberated. Thus, for every pound of carbon which undergoes incomplete combustion (14,650–4,430) or 10,220 B.t.u. are wasted. Therefore, the presence of carbon monoxide in the flue gases (Sec. 483) indicates a loss of available heat energy in the flue gases.

467. Table Showing Properties Of Combustible Substances. (The values shown in the table are based on the combustion of 1 lb. of the substance.)

Substance	Chem. formula and combining wts.	Wt. in lb. required for the burning of the substance		Products of comb. when burned in air	Wt. in lb. of products of combustion when burned in air	Volume of prod. of comb. expressed as percentage of total volume of air	Heat of combustion or heat energy liberated, in B.t.u.
		Oxygen	Air				
Carbon (complete combustion)	$C + O_2 = CO_2$ $12 + 32 = 44$	2.67	11.61	Carbon dioxide Nitrogen	3.67 8.94	21 79	14,650
Hydrogen......................	$2H_2 + O_2 = 2H_2O$ $4 + 32 = 36$	8	34.80	Water vapor Nitrogen	9.00 26.80	42 79	62,100
Sulphur.......................	$S + O_2 = SO_2$ $32 + 32 = 64$	1	4.35	Sulphur dioxide Nitrogen	2.00 3.35	21 79	4,000
Carbon (incomplete combustion)...	$2C + O_2 = 2CO$ $24 + 32 = 56$	1.33	5.79	Carbon monoxide Nitrogen	2.33 4.46	42 79	4,430
Carbon monoxide................	$2CO + O_2 = 2CO_2$ $56 + 32 = 88$	0.57	2.48	Carbon dioxide Nitrogen	1.57 1.91	42 79	4,380

468. If Carbon Dioxide (CO_2) Is Passed Over Incandescent Carbon (C) each molecule of carbon dioxide will join with a molecule of carbon and form two molecules of carbon monoxide (CO). This chemical reaction is expressed by the following formula:

$$C + CO_2 = 2CO \tag{323}$$

$$12 + 44 = 56 \tag{324}$$

The numbers in For. (324), which are the combining weights of the substances, show that 1 lb. of carbon (C) combines with 3.67 lb. of carbon dioxide (CO_2) and forms 4.67 lb. of carbon monoxide. If measured at the same temperature and pressure, the volume of the carbon monoxide (CO) thus formed will be twice that of the carbon dioxide (CO_2). Instead of this reaction liberating heat energy, it absorbs heat energy—heat energy must be supplied to produce it. The amount of heat energy which is absorbed in reducing 1 lb. of carbon dioxide to carbon monoxide by the above process is about 1,580 B.t.u. A thermochemical equation for this reaction is therefore:

$$0.273\ lb.\ C + 1\ lb.\ CO_2 = 1.273\ lb.\ CO - 1{,}580\ B.t.u. \tag{325}$$

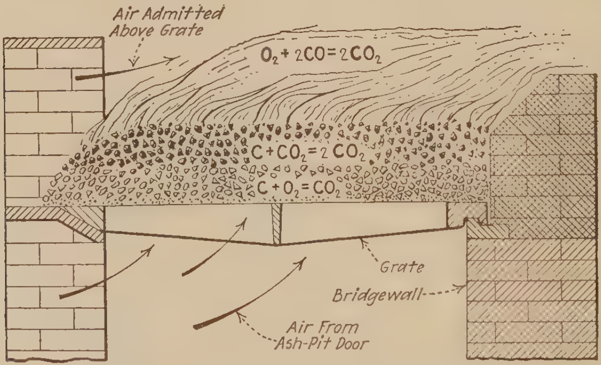


Fig. 411.—Combustion on a coal-burning grate.

Note.—The Chemical Reactions Which Occur, To Some Extent At Least, In A Coal-burning Furnace are represented in Fig. 411. When the oxygen from the air, which is supplied by the draft, comes in contact with the hot coals on the grate, the union of the carbon and the oxygen (Sec. 465) forms carbon dioxide and liberates heat energy. This reaction is expressed by For. (322). See also Fig. 411. As this carbon dioxide gas passes through the upper layer of incandescent coal (which is constituted largely of carbon, Div. 13) where the air (oxygen) supply is restricted, it is reduced to carbon monoxide as explained above (For. 325). This process absorbs heat. The carbon monoxide thus formed continues to rise through the glowing coal to the top of the fuel bed. Then, if a sufficient quantity of air is admitted above the grate the carbon monoxide will be burned to carbon dioxide (Table 467). This process releases heat energy. If by the above described process, 1 lb. of carbon is burned to carbon dioxide, the total heat energy liberated, the total weight of air used, and the weight of the carbon dioxide which is formed will be the same as though the 1 lb. of carbon had been directly burned to carbon dioxide (Sec. 465).

469. The Heating Value Of A Coal May Be Computed From The Ultimate Analysis (A. S. M. E. POWER PLANT TEST CODE, 1915) by the following formula:

$$(326) \quad \mathbf{H} = 14{,}600C + 62{,}000\left(H - \frac{O}{8}\right) + 4{,}000S \qquad \text{(B.t.u. per lb.)}$$

Wherein: **H** = heating value of the coal, in British thermal units per pound. C, H, O, and S, = respectively, the weights in pounds, of the carbon, hydrogen, oxygen, and sulphur, which as shown by the ultimate analysis (Sec. 455), are contained in 1 lb. of the coal. See the note and the examples below. The above values of 14,600 B.t.u. per pound of carbon, 62,000 B.t.u. per pound of hydrogen do not quite agree with the corresponding values given in Table 467. The reason for this is, doubtless, that the values in For. (326) are those which have been found by experiment to give the most-nearly, correct heating values for the most of the more common coals, whereas those in Table 467 are the values which have been determined by experiment for the pure elements. Also it is a fact that the quantity of heat which is liberated by the combustion of a compound may be more or less than the heat which would be liberated by the combustion of the elements which form the compound. And furthermore, for the same reactions, the values which have been obtained by different authorities vary from one another.

NOTE.—THE WEIGHTS, IN POUNDS, OF THE VARIOUS CONSTITUENTS OF A FUEL WHICH ARE CONTAINED IN 1 LB. OF THE FUEL may be obtained by dividing the percentage values of the ultimate analysis (Sec.

455) by 100. Thus, if the ultimate analysis shows that a certain fuel contains 88.86 per cent. of carbon, each pound of the fuel contains: 88.68 ÷ 100 = 0.886,8 *lb. of carbon.*

EXAMPLE.—The ultimate analysis of anthracite coal (Wilkesbarre, Pa.) from Table 451 shows the following percentages: carbon, 88.86; hydrogen, 2.04; oxygen, 1.95; and sulphur, 0.35. What is the heating value of this coal, in British thermal units per pound, based on the results of the ultimate analysis?

SOLUTION.—By For. (326): *the heating value,* $\mathbf{H} = 14{,}600C + 62{,}000(H - O/8) + 4{,}000S = (14{,}600 \times 0.8886) + 62{,}000[0.0204 - (0.0195 \div 8)] + (4{,}000 \times 0.0035) = 12{,}974 + 1{,}116 + 14 = 14{,}104$ *B.t.u. per lb.* Note that this value is $(14{,}104 - 13{,}950) = 154$ *B.t.u. per lb.* greater than that given in Table 451. Thus, if the calorimetric value as given in Table 451, is taken as correct, the computed value is in error by about 1.1 per cent.

470. The Weight Of Oxygen Which Is Theoretically Required For The Complete Combustion Of A Fuel may be computed by the following formula:

$$\mathbf{W}_O = 2.67C + 8\left(H - \frac{O}{8}\right) + S \qquad \text{(lb.)} \tag{327}$$

Wherein: $\mathbf{W}_O$ = weight, in pounds, of oxygen which is theoretically required for the complete combustion of 1 lb. of fuel. C, H, O, and S = respectively, the weights, in pounds, of the carbon, hydrogen, oxygen, and sulphur which are contained in 1 lb. of the fuel, as shown by the ultimate analysis (Sec. 455).

DERIVATION.—The complete combustion of 1 lb. of carbon (Sec. 465) requires 2.67 lb. of oxygen. Therefore, if 1 lb. of a certain coal contains C lb. ($100C$ per cent.) of carbon, then the weight, in pounds, of oxygen required to burn the carbon in 1 lb. of the coal is $2.67 \times C$. By a similar line of reasoning *S lb.* of oxygen will be required to burn the sulphur in 1 lb. of the coal. It is assumed that all of the oxygen which the ultimate analysis shows the coal to contain, is already combined with a part of the hydrogen and exists in the form of water of crystallization (H_2O). Therefore, this part of the hydrogen which has already combined with oxygen cannot combine with any more oxygen, and, hence, it is incombustible. Since hydrogen and oxygen combine (Table 467) in the ratio of 1 part hydrogen to 8 parts oxygen, the weight of the free hydrogen in 1 lb. of coal which is available for combining with the supplied oxygen is $(H - O/8)$. Consequently (Table 467) the number of pounds of oxygen which is required to combine with $(H - O/8)$ pounds of hydrogen is $8(H - O/8)$ pounds. Thus (*The number of pounds of oxygen required to burn the carbon in* 1 *lb. of a fuel*) + (*The number of pounds of oxygen required to burn the free hydrogen in* 1 *lb. of the fuel*) + (*The number of* *pounds of oxygen required to burn the sulphur in* 1 *lb. of fuel*) = *The total weight of oxygen which is theoretically required to burn* 1 *lb. of the fuel.* Or, expressing this symbolically, For. (327) results.

EXAMPLE.—What is the weight of oxygen which is theoretically required to burn 20 lb. of anthracite coal (Wilkesbarre, Pa. Table 451)? SOLUTION.—From Table 451, anthracite coal (Wilkesbarre, Pa.) contains, 88.86 per cent. of carbon, 2.04 per cent. hydrogen, 1.95 per cent. oxygen and 0.35 per cent. sulphur. That is 1 lb. of this coal contains the following weights of the various substances: carbon, 0.888,6 lb.; hydrogen, 0.020,4 lb.; oxygen, 0.019,5 lb.; sulphur, 0.003,5 lb. By For. (327): *The weight of the oxygen which is theoretically required to burn* 1 *lb. of the fuel,* $W_o = 2.67C + 8(H - O/8) + S = 2.67 \times 0.888{,}6 + 8(.020{,}4 - 0.019{,}5 \div 8) + 0.003{,}5 = 2.372{,}5 + 0.144{,}0 + 0.003{,}5 = 2.52$ *lb.* Therefore, *the weight of oxygen which is required to burn* 20 *lb. of the fuel* $= 20 \times 2.52 = 50.4$ *lb.*

471. The Weight Of Dry Air Which Is Theoretically Required For The Complete Combustion Of A Coal may be computed by the following formula. This formula follows from For. (327) by multiplying it by the value "4.35," the ratio of air weight to oxygen weight as explained in Sec. 464; that is, 4.35 lb. of air must be used for each 1 lb. of oxygen which is required.

$$W_A = 11.61C + 34.80\left(H - \frac{O}{8}\right) + 4.35S \qquad \text{(lb.)} \tag{328}$$

Wherein: W_A = the weight, in pounds, of air which is theoretically required to burn 1 lb. of the coal. C, H, O, and S = respectively, weights in pounds of the carbon, hydrogen, oxygen, and sulphur, which, as determined from the ultimate analysis, are contained in 1 lb. of the fuel.

EXAMPLE.—What weight of air would be theoretically required for the complete combustion 1 ton (2,000 lb.) of the Wilkesbarre, Pa. anthracite coal (Table 451)? SOLUTION.—By Table 451: $C = 0.886{,}5$, $H = 0.020{,}4$, $O = 0.019{,}5$, and $S = 0.003{,}5$. By For. (328): *The weight of air which is theoretically required for the complete combustion of* 1 *lb. of the coal,* $W_A = 11.61C + 34.80\ (H - O/8) + 4.35S = (11.61 \times 0.886{,}5) + 34.80\ [0.020{,}4 - (0.019{,}5 \div 8)] + (4.35 \times 0.003{,}5) = 10.292{,}3 + 0.626{,}4 + 0.015{,}2 = 10.934{,}0$ *lb.* Therefore, *the weight of air which is theoretically required for the complete combustion of* 1 *ton of this coal* $= 2{,}000 \times 10.934{,}0 = 21{,}868$ *lb.*

472. The Amount Of Air Which Must Actually Be Supplied For Approximately Complete Combustion Is Considerably Greater Than That Which Is Theoretically Necessary (Sec.

471). For oxygen to unite with carbon, the oxygen molecules must come in intimate contact with the carbon molecules for an appreciable period of time. To get an oxygen molecule to come in intimate contact with each of the carbon molecules, a much greater number of oxygen molecules must be supplied than are theoretically necessary. When the oxygen for combustion is obtained from the air, the presence of the nitrogen molecules tends to prevent the oxygen molecules from contacting with the carbon. Also this intimate contact is further retarded by the irregularity in the passage of air through the fuel bed due to uneven thickness of the fire, variation in the size of the coal, clinkers, ashes. and the like.

Note.—Most Efficient Combustion Of Coal Is Obtained When The Air Supplied Is From About 30 To 50 Per Cent. Greater Than That Which Is Theoretically Required. The amount of excess air which should be supplied will vary over wide limits, depending upon the design of the furnace, the kind of coal which is being burned, and the manner of firing the coal. As will be shown hereinafter, too much air or too little air will result in a waste of heat energy which can ordinarily be prevented by careful and intelligent firing. The amount of excess air for the most economical combustion must be determined by trial for each individual case.

473. The Flue Gases, Or The Products Of Combustion Of Coal when completely burned in oxygen will consist of (1) *Carbon dioxide*. (2) *Water vapor*. and (3) *A little sulphur dioxide* or sulphur trioxide. If a part of the carbon is incompletely burned, the flue gases, in addition to the above, will contain some *carbon monoxide*. In the ordinary coal-burning furnace where the oxygen for combustion (Sec. 464) is obtained from the air, the flue gases will consist principally of *carbon dioxide*, *carbon monoxide*, *water vapor*, *nitrogen*, and *oxygen*. Nitrogen is present in the flue gases because the nitrogen of the air is incombustible (Sec. 463) and is not changed in passing through the furnace. Oxygen is present because, due to the excess of air (Sec. 472), all of the oxygen cannot combine with the combustibles of the coal. Hence, some of the oxygen passes unchanged through the fuel bed and into the flue gases. The sulphur dioxide or sulphur trioxide composes such a small percentage of the flue gases that it is usually disregarded.

474. Flue-gas Analysis consists in determining the percentage by volume of the carbon dioxide, carbon monoxide, oxygen, and nitrogen. There are various methods of making this determination. One method is briefly described in the following section. As shown hereinafter in this division, *the results of a flue-gas analysis may be used to determine whether or not the fuel is being economically burned.*

In this apparatus, as is explained below, a known volume of the flue gas to be tested is forced successively into the glass pipettes *C*, *D*, and *E*. Each of these pipettes contains a chemical which will absorb certain of the gas constituents of the flue gas. Thereby the percentage by volume of each of the constituents can be measured.

475. The Most Common Method Of Making A Flue Gas Analysis Is By Means Of The Orsat Apparatus (Fig. 412).

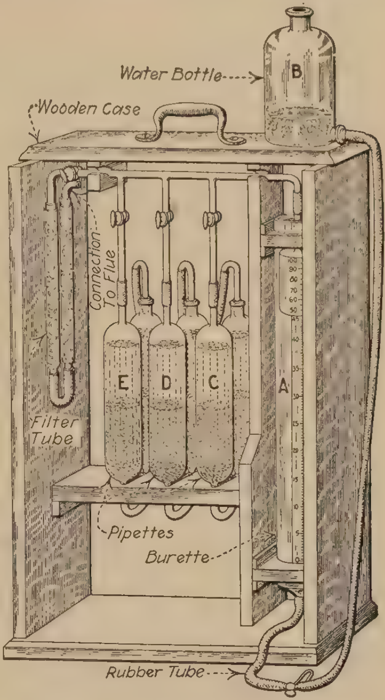


FIG. 412.—Orsat apparatus for analyzing flue gases.

EXPLANATION.—By manipulating the water bottle, *B*, (Fig. 412) exactly 100 c.c. (cubic centimeters) of the flue gas which is to be analyzed is drawn into the graduated burette, *A*. By again manipulating the water bottle, this 100-c.c. gas sample is passed into and out of the treating pipette, *C*, several times. Pipette *C* contains a solution of potassium hydroxide which absorbs the carbon dioxide that is in the flue gas. After all of the carbon dioxide has thus been removed from the flue gas sample, the remainder of the sample is passed back into *A* and measured. Since the carbon dioxide has been removed, the gas which still remains will have a volume which is somewhat less than 100 c.c. The decrease in volume indicates the percentage, by volume, of the carbon dioxide (CO_2) in the flue gas.

In like manner the remainder of the gas is introduced into pipette *D*, which contains a solution of potassium pyrogallate. The potassium pyrogallate absorbs the oxygen from the flue gas sample. After the oxygen has been removed, the remainder of the gas is passed into pipette *E* which contains an acidulated solution of cuprous chloride. This absorbs the carbon monoxide. The shrinkage in volume, in each case indicates, respectively, the percentage by volume, of oxygen and carbon monoxide. After the carbon dioxide, oxygen, and carbon monoxide have been removed from the flue gas sample, the remainder consists principally of nitrogen. Although this remainder consists of nitrogen and a small quantity of other gases, it is, in the flue gas analysis, called nitrogen.

Example.—Assume that 100 c.c. of the flue-gas sample is originally drawn into burette *A* of Fig. 412. After the sample has been passed through pipette *C* a number of times and then measured, it is found that the volume is now 88 c.c. Thus, the sample contains: 100 − 88 = 12 *c.c. of carbon dioxide*, or the proportion by volume of the carbon dioxide is $^{12}\!/_{100}$, or 12 per cent. After the oxygen has been removed by passing the remainder of the sample through pipette *D*, the volume as measured in *A* is 82 c.c. That is there were: 88 − 82 = 6 *c.c. of oxygen* in the original 100 c.c. of the gas, or the proportion by volume, of the oxygen is 6 per cent. After the remainder of the sample has had the carbon monoxide removed by passing it into pipette *E*, the volume is found to be 81.4 c.c. Thus, the proportion by volume of the carbon monoxide is: 82 − 81.4, or 0.6 per cent. Since, there are 81.4 c.c. yet remaining, the percentage, by volume, of nitrogen is 81.4 per cent.

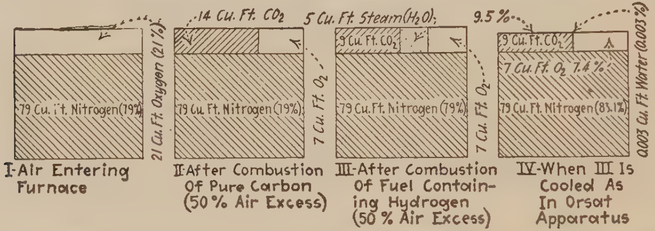

79 Cu. Ft. Nitrogen (79%)
21 Cu. Ft. Oxygen (21%)
I-Air Entering Furnace
14 Cu. Ft. CO₂
79 Cu. Ft. Nitrogen (79%)
7 Cu. Ft. O₂
II-After Combustion Of Pure Carbon (50% Air Excess)
5 Cu. Ft. Steam (H₂O)
9 Cu. Ft. CO₂
79 Cu. Ft. Nitrogen (79%)
7 Cu. Ft. O₂
III-After Combustion Of Fuel Containing Hydrogen (50% Air Excess)
9.5%
9 Cu. Ft. CO₂
7 Cu. Ft. O₂ 7.4%
79 Cu. Ft. Nitrogen (83.1%)
0.003 Cu. Ft. Water (0.003%)
IV-When III Is Cooled As In Orsat Apparatus

Fig. 413.—Showing changes in the composition of 100 cu. ft. air which are drawn into a boiler furnace and used to burn the fuel.

Note.—The Flue-gas Analysis Does Not Reveal All Of The Products Of Combustion (Fig. 413)—the water vapor (H_2O) is condensed and therefore is not measured. The flue-gas apparatus therefore analyzes only the *dry part* of the flue gases. For this reason the percentage by volume of the nitrogen as determined by the flue-gas analysis will always be greater than 79 which is (Sec. 464) the percentage by volume of nitrogen in the air. The nitrogen must necessarily constitute a larger portion of the dry gases than of the total. Stated in another form: *The sum of (the percentage by volume of the carbon dioxide) + (That of the* *oxygen) + (½ that of the carbon monoxide) will always be less than* 21. From the preceding it is obvious that, with a fuel containing hydrogen, it is impossible to get the full 21 per cent. of CO_2 in the flue gases, even with perfect combustion and no excess air. Some engineers erroneously believe that 21 per cent. is the ideal.

476. The Weight Of Air Which Is Actually Being Supplied For Burning Each Pound Of Fuel may be computed with commercial accuracy (see note below) by the following formula:

$$(329) \qquad W_A = 3.036C\frac{N}{CO_2 + CO} \qquad \text{(pounds)}$$

Wherein: W_A = weight of air, in pounds, which is being supplied to the furnace for each pound of coal which is being burned at the time the flue gas sample was taken. C = number of pounds of carbon contained in 1 lb. of coal as determined from the ultimate analysis. N, CO_2, and CO = the respective percentages, by volume, of the nitrogen, carbon dioxide, and carbon monoxide as obtained by the flue-gas analysis (Sec. 475). If any of the carbon which is in the coal is unburned and is removed from the grate in the ashes, then C should be taken as the weight of carbon actually burned per pound of fuel consumed.

Note.—The Only Method Whereby The Amount Of Combustible Which Is Contained In The Ashes May Be Exactly Determined Is By An Analysis Of A Sample of the refuse from the furnace. The above formula will result in only approximate values, since in its derivation, the air which enters the furnace is assumed to be dry and the only combustible which is considered to be in the fuel is carbon. Thus the hydrogen and the sulphur content of the coal is neglected. However, for most coals, the application of For. (329) will result in a value which is sufficiently accurate for all practical purposes; the error in using it does not ordinarily exceed 0.2 per cent.

477. The Percentage Excess Of The Air Which Is Being Supplied Above That Which Is Theoretically Required may be determined by the following formula:

$$(330) \qquad X = \left(\frac{N}{N - 3.782(O - \frac{1}{2}CO)} - 1\right) \times 100 \qquad \text{(per cent.)}$$

Wherein: X = percentage of excess air above that which is theoretically required. N, O, and CO = respectively, the percentages, by volume, of the nitrogen, oxygen, and carbon monoxide as obtained by the flue-gas analysis.

478. The Weight Of The Dry Flue Gases Per Pound Of Coal Burned may be computed by the following formula:

$$(331) \qquad W_P = \left[\frac{11CO_2 + 8O + 7(CO + N)}{3(CO_2 + CO)}\right]C \qquad \text{(lb.)}$$

Wherein: W_P = weight, in pounds, of the dry flue gases per pound of coal burned. CO_2, O, CO, and N = respectively, the percentages by volume of carbon dioxide, oxygen, carbon monoxide, and nitrogen from the flue-gas analysis. C = weight, in pounds, of carbon which is burned per pound of fuel. If there is no loss of carbon to the ashes (Sec. 482), the weight of gas, W_P, determined by the above formula is per pound of dry or moist fuel as the percentage of carbon from which C is determined is referred to a dry or moist basis.

479. The Theoretical Temperature Produced By Combustion with dry air of dry coal containing no hydrogen may be computed by the following formula:

$$(332) \qquad T = T_A + \frac{H}{0.24W_P} \qquad \text{(deg. F.)}$$

Wherein: T = the temperature, in degrees Fahrenheit, which is produced by combustion of the fuel. T_A = temperature, in degrees Fahrenheit, of the air entering the furnace. H = heating value, in British thermal units per pound, of the coal as determined by For. (326). W_P = the weight, in pounds, of the products of combustion per pound of fuel burned as determined by For. (331). The value of 0.24 is taken as the mean specific heat of the products of combustion over the temperature range from T_A to T. However, due to radiation, to the fact that all coals contain moisture and hydrogen, and that the air always contains some moisture, and to other losses, this theoretical temperature can never be attained in practice. The temperatures actually attained in a boiler furnace, under normal conditions, are likely to be in the neighborhood of those suggested in Fig. 64.

480. The Chemical Energy Of A Fuel Is Not All Utilized In A Boiler.—Only a portion of the fuel's chemical energy is actually liberated and transferred to the water and steam in the boiler. The balance of the chemical energy is wasted, partly as chemical energy and partly as heat energy. Hence the energy of the fuel is divided in the boiler into two parts: (1) *Heat utilized.* (2) *Energy wasted.* The wasted energy is often called the heat loss. The different ways in which energy is wasted are described in Sec. 481. A *heat balance* (Sec. 489) is a tabulation which shows how the chemical energy of the fuel is divided into utilized heat and various losses.

481. The Heat Losses In A Steam-boiler Furnace occur through the following channels: (1) *Unburned fuel in the ash.* (2) *Combustible in the flue gas,* usually in the form of carbon monoxide, Sec. 466. (3) *Heat carried away in the dry flue gases.* (4) *Free moisture in the coal.* (5) *Moisture formed by burning the free hydrogen in the coal to water vapor.* (6) *Moisture in the air which is supplied to the furnace.* (7) *Radiation and unaccounted losses.* Each of these losses is discussed in following sections.

482. The Heat Loss Due To The Unburned Fuel In The Ash may be computed by the following formula, which is based on the assumption that all of the unburned combustible which drops from the grate to the ash pit is carbon:

$$\mathbf{H}_A = 14{,}650AC \qquad \text{(B.t.u. per lb.)} \tag{333}$$

Wherein: $\mathbf{H}_A$ = the heat, in British thermal units, which is lost for each pound of coal burned because of unburned carbon rejected in the ashes. A = weight, in pounds, of ash per pound of coal, as determined by the ultimate analysis of the coal. C = weight, in pounds of carbon per pound of ash, as determined by analysis of the ashes which are rejected from the furnace. Whether or not this loss is large or small will depend upon the grate or stoker, the kind and size of coal being fired, the rate of combustion, and upon the care which is exercised by the fireman. In practice, this loss varies from practically zero to 15 or 20 per cent. of the heating value of the coal. It reaches these maximum values only when the rate of combustion is excessive, due to large overloads, or when the firemen grows careless. An average value for good practice would probably be 3 to 5 per cent.

483. The Heat Loss Which Is Occasioned By Carbon Monoxide Escaping In The Flue Gases (Secs. 466 and 468) may be read from Fig. 414 or it may be computed by the following formula:

$$\mathbf{H}_{CO} = 10{,}220 \times \frac{CO}{CO_2 + CO} \times C \qquad \text{(B.t.u. per lb.)} \tag{334}$$

Wherein: $\mathbf{H}_{CO}$ = the heat, in British thermal units, which is lost from each pound of coal burned due to carbon monoxide which escapes with the flue gases. CO and CO_2 = respectively, the percentages by volume of the carbon dioxide and the carbon monoxide as obtained by the flue-gas analysis (Sec. 475). C = weight, in pounds, of carbon actually burned per pound of fuel consumed. If the amount of carbon which leaks into the ash pit (Sec. 482) is small, C may be taken from the ultimate analysis values without causing any appreciable error. In general, the loss due to carbon monoxide is negligible (see also Sec. 494).

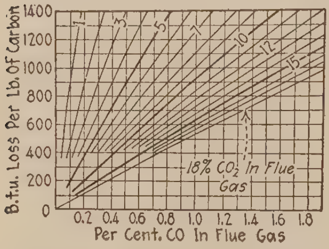


FIG. 414.—Graphs for finding heat loss due to CO in the flue gases (H. O'NEILL in *Power*).

484. A Considerable Quantity Of Heat Is Carried Out Of The Furnace By The Flue Gases.—The air and fuel are admitted to the furnace at a temperature somewhere near that of the boiler room. They leave the furnace, in the form of products of combustion, by way of the stack at a temperature somewhere around 500° F. The heat which is thus lost may be computed by the following formula:

$$\mathbf{H}_P = 0.24\mathbf{W}_P\ (T_2 - T_1) \qquad \text{(B.t.u. per lb.)} \tag{335}$$

Wherein: $\mathbf{H}_P$ = heat, in British thermal units, which is lost in the escaping flue gases for each pound of fuel which is burned. $\mathbf{W}_P$ = weight, in pounds, of the products of combustion for each pound of fuel burned as determined by For. (331), Sec. 478. T_2 = temperature, in degrees Fahrenheit, of the flue gases measured at the point where the products of combustion leave the boiler. T_1 = temperature, in degrees Fahrenheit, of the air supplied to the furnace. 0.24 = the mean specific heat at constant pressure (approximately) of the flue gases. The loss due to this source cannot be eliminated. It can be minimized by keeping both W_P and T_2 at the lowest reasonable values. Since W_P depends on the percentage of excess air, and since without sufficient excess air the other losses become excessive, some reasonable value of W_P (somewhat in excess of the theoretical) must be tolerated; see Fig. 415. Likewise, since the value of T_2 usually determines the draft pressure (Sec. 256) here too a compromise must be made. In *good* practice the heat loss due to the heating of the flue gases can be reduced to about 15 per cent.

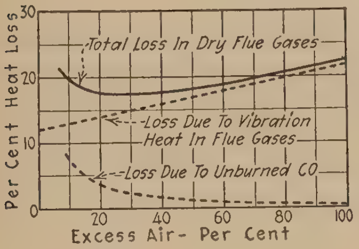


FIG. 415.—Showing how losses in dry flue gases vary with the percentage of excess air. The values shown are not to be taken as representative. The *variation*, however, is shown about as it usually occurs.

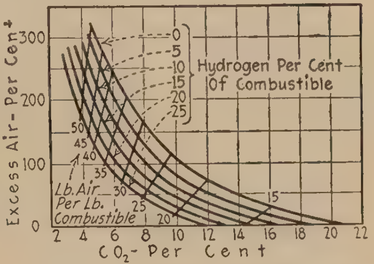


FIG. 416.—Graphs showing percentages of excess air corresponding to different CO_2 percentages for fuels containing hydrogen.

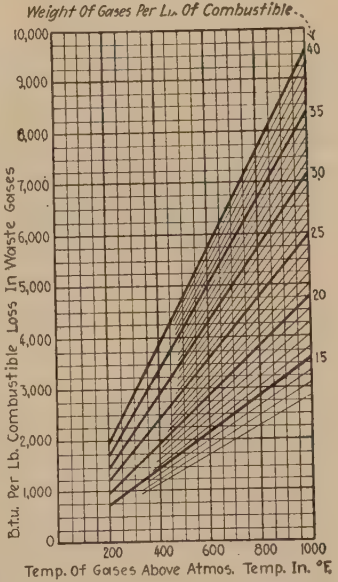


FIG. 417.—Graphs for finding heat loss in dry flue gases. (See example in text.)

EXAMPLE.—A GRAPHICAL METHOD OF FINDING THE HEAT LOSS IN THE DRY FLUE GASES involves the use of the charts of Fig. 416 and 417. Suppose a given fuel contains 10 per cent. of hydrogen per lb. of combustible and that a flue-gas analysis shows 11 per cent. CO_2. Then, by Fig. 416, the combustion requires 20 lb. of air per lb. of combustible. Therefore, the weight of gases per pound of combustible will be (20 + 1) = 21 *lb.* Now, if the temperature of the flue gases is 560° F. and atmospheric temperature is 60° F., then by Fig. 417, at the intersection of the 21 lb. and the 500° F. lines, the *heat loss* = 2,500 *B.t.u.* per pound of combustible.

485. The Heat Which Is Lost Through The Free Moisture Contained In The Coal (Fig. 418) is occasioned by the fact that the temperature of the moisture must be raised from that of the coal when fired to about 212° F., then evaporated, and then to the temperature of the escaping flue gas. The quantity of heat which is thus lost per pound of fuel burned may be computed by:

$$(336)\quad \mathbf{H}_M = M[(212 - T_1) + 970.4 + 0.48(T_2 - 212)] \quad \text{(B.t.u. per lb.)}$$

Wherein: $\mathbf{H}_M$ = the heat, in British thermal units, which is lost per pound of fuel burned because of the free moisture which is contained in the coal. M = weight, in pounds, of the moisture in each pound of coal as determined by the proximate analysis of the coal as fired. T_1 and T_2 = respectively, the temperature, in degrees Fahrenheit, of the boiler room and of the escaping flue gases (Sec. 661). The loss due to moisture in the coal cannot be eliminated. It is minimized when the flue gases leave the boiler at the reasonable minimum temperature (Sec. 484). In good practice this loss seldom exceeds 1 to 2 per cent.

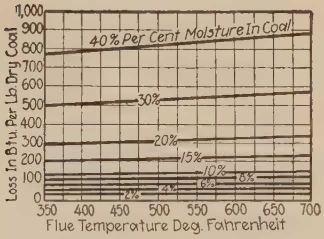


FIG. 418.—Graphs showing loss due to moisture in coal for a boiler-room temperature of 80° F. (H. O'NEILL in *Power.*)

DERIVATION of For. (336). The expression "$(212 - T_1)$" represents the heat required to raise 1 lb. of water, which has a specific heat of "1," from the boiler-room temperature up to the boiling point. The value "970.4" is the latent heat of vaporization of 1 lb. of water. The expression "$0.48(T_2 - 212)$" represents the heat required to increase the temperature of 1 lb. of the vapor from the vaporizing temperature, 212° F., up to the temperature of the flue gases.

486. There Is A Real Loss From The Furnace Due To The Water Vapor Which Is Formed By The Burning Of The Hydrogen In The Coal (Table 467 and Fig. 419). This unpreventable loss results from the same reasons as those outlined in Sec. 485 for the free moisture contained in the coal. It may be computed by the following formula:

$$(337)\quad \mathbf{H}_H = 9H[(212 - T_1) + 970.4 + 0.48(T_2 - 212)] \quad \text{(B.t.u. per lb.)}$$

Wherein: $\mathbf{H}_H$ = heat, in British thermal units, which is lost per pound of fuel burned due to the hydrogen content of the fuel. H = the weight, in pounds of hydrogen per pound of fuel, as determined by the ultimate analysis (Sec. 455). T_1 and T_2 = respectively, the temperature, in degrees Fahrenheit, of the boiler room and the temperature of the escaping flue gases. The loss due to hydrogen cannot be eliminated. It can be minimized by cooling the flue gases, in the boiler, to a reasonable minimum value (Sec. 484). In good practice, this loss runs from practically zero for anthracite coals to about 4 per cent. for coals high in hydrogen.

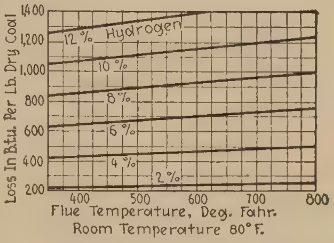


Fig. 419.—Graphs showing loss due to hydrogen in coal. (H. O'Neill in *Power.*)

Derivation.—The weight of water formed is always 9 times that of the hydrogen from which it is formed. The derivation of the remainder of the equation will be obvious from that given under For. (336).

487. There Will Also Be A Heat Loss Occasioned By The Moisture Contained In The Air.—This moisture is already in the form of vapor when it enters the furnace. Consequently, the heat of the liquid (Sec. 363) and the latent heat of vaporization (Sec. 364) do not have to be added to this moisture. Therefore, the only heat which is carried out of the furnace by the moisture (water vapor) in the air is that which is necessary to raise its temperature from that of the ingoing air to that of the escaping flue gases. This loss may be computed by the following formula:

$$(338)\qquad \mathbf{H}_V = 0.47\ \mathbf{W}_V\mathbf{W}_A(T_2 - T_1) \quad \text{(B.t.u. per lb.)}$$

Wherein: $\mathbf{H}_V$ = the heat, in British thermal units, which is lost per pound of fuel burned, due to the moisture in the air. $\mathbf{W}_V$

= weight, in pounds, of moisture per pound of air supplied to the furnace. This value can be obtained by means of a wet-and-dry-bulb thermometer and psychrometric chart (see Div. 10). $\mathbf{W}_A$ = weight of air, in pounds, per pound of fuel as obtained from For. (329), Sec. 476. T_1 and T_2 = respectively, the temperatures, in degrees Fahrenheit, of the air entering the ash pit and of the escaping flue gases. 0.47 = the mean specific heat of steam between the temperatures T_1 and T_2 and at atmospheric pressure. This loss is comparatively small and is frequently not computed. It may be minimized by keeping $\mathbf{W}_A$ at a reasonable minimum (see Sec. 484). In good practice it seldom exceeds 1 per cent. When not computed, it is included in the unaccountable losses (Sec. 488).

488. The Losses Of Heat From The Furnace Which Are Due To "Radiation And Unaccounted Losses" ($\mathbf{H}_R$ in For. (339) are either impossible or impracticable to compute. These losses include: (1) *Radiation loss.* This loss will vary with the size of the unit, the condition of the setting and the like. It may be decreased by jacketing with a non-conducting material. (2) *Loss due to unburned volatile hydrocarbons* (see Sec. 494). (3) *Loss due to the hydrogen which may be formed by the chemical union of carbon and moisture* ($C + H_2O = CO + H_2$). (4) *Other losses not otherwise accounted for as, for example, the errors in observations.* These "radiation and unaccounted losses" are computed, in an evaporation test, by: 100 − (boiler efficiency + the percentages of six losses as outlined in Secs. 481 to 487) = *percentage of radiation and unaccounted losses.* The magnitude of these losses varies, in good practice, from about 2 to 3 per cent. for very large boilers operating at high rates, to 7–8 per cent. for medium sized boilers, and 12–15 per cent. for small boilers operating at low rates.

489. The "Heat Balance" For A Boiler Furnace is, as was suggested in Sec. 488, a tabulation of the utilized heat and the several losses which occur at the boiler. The heat balance may be written as a formula, thus:

$$(339)\quad \mathbf{H} = \mathbf{H}_U + (\mathbf{H}_A + \mathbf{H}_{CO} + \mathbf{H}_P + \mathbf{H}_M + \mathbf{H}_H + \mathbf{H}_V + H_R) \quad \text{(B.t.u. per lb.)}$$

Wherein: $\mathbf{H}$ = heating value of the fuel, in British thermal units per pound, as determined by analysis or calorimeter test. $\mathbf{H}_U$ = the heat utilized in evaporating water from each pound of fuel, in British thermal units. $\mathbf{H}_R$ = the heat lost per pound of fuel due to radiation and unaccounted for, in British thermal units. The other symbols having the same meanings as in Fors. (333) to (338).

EXAMPLE.—The values of the various losses and of the heat utilized during a typical boiler trial are pictured in Fig. 420.

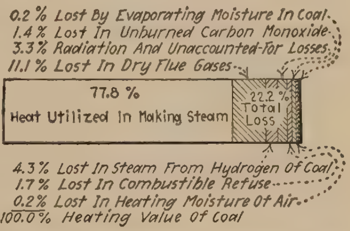


FIG. 420.—Chart showing heat balance as determined by test on a 2400-hp. boiler operating at 137 per cent. of rated load. This chart shows very good operation.

490. The Formula For Boiler Efficiency or, more properly "the boiler, furnace, and grate efficiency," follows directly from For. (339). (See also Sec. 499 for another equivalent method of expressing this efficiency.) Thus, since it is always true that: *Efficiency* = (*Output*) ÷ (*Input*), it follows that:

$$(340)\qquad \mathbf{E} = \frac{(Heat\ value) - (Losses)}{Heat\ value} = \frac{Heat\ utilized}{Heat\ value}$$

Now, since the portion of For. (339) which is included in the parentheses represents the losses, it follows that:

$$(341)\qquad \mathbf{E} = \frac{\mathbf{H} - Losses}{\mathbf{H}} = \frac{\mathbf{H}_U}{\mathbf{H}} \qquad \text{(decimal)}$$

Wherein: $\mathbf{E}$ = the efficiency of the boiler, furnace, and grate, expressed as a decimal. The other symbols have the same meanings as in the preceding.

EXAMPLE.—If the heating value of a coal is 14,000 B.t.u. per lb. and of this, the heat utilized in a certain boiler installation in evaporating the water is 10,892 B.t.u. per lb., what is the efficiency of the boiler? SOLUTION.—Substitute in For. (341): $\mathbf{E} = \mathbf{H}_U/\mathbf{H} = 10{,}892 \div 14{,}000 =$ 77.8 *per cent.* = *boiler efficiency.* See also Fig. 420.

491. The Rate Of Combustion Of Coal is usually considered to be the number of pounds of coal burned per square foot of grate surface per hour. The rate of combustion depends upon the draft pressure, the kind of coal being burned, the design of the furnace, and the skill of the fireman. If the fuel bed is kept at the proper thickness (4 to 14 in., depending on the kind of coal) the rate of combustion will be increased if the quantity of air which flows through the fire is increased; the rate will be decreased if the air flow is decreased. Roughly, the rates of combustion for different fuels, in pounds per square foot of grate surface per hour, are (1) *Anthracite*, 15. (2) *Semi-anthracite*, 16. (3) *Semi-bituminous*, 18. (4) *Eastern-bituminous*, 20. (4) *Western-bituminous*, 30.

492. The Efficient Or Inefficient Burning Of Coal In Boiler Furnaces depends upon whether or not the greatest possible amount of the heat which is releasable by combustion (Sec. 452) is utilized in evaporating the water in the boiler. Some of the chemical energy of the fuel will always be wasted. However, the amount which is wasted is, to a large extent, within the control of the fireman. The moisture losses (Secs. 485, 486 and 487) cannot ordinarily be controlled by the fireman. These are sometimes called the *unpreventable losses*. The heat loss which is caused by carbon being rejected in the ashes (Sec. 482), that which is caused by being carried out by the flue gas (Sec. 484), and that which is caused by carbon monoxide escaping in the flue gas (Sec. 483), cannot be entirely eliminated. But, since they may be minimized by proper firing, they are sometimes called the *preventable losses*. Thus, by exercising proper care in handling the coal and in clearing the fire, the amount of coal (unburned carbon) which is rejected in the ashes may be reduced to a minimum. The stack losses (Sec. 484) and the unburned combustible in the flue gas (Sec. 483) are discussed in the following sections.

493. In General, The Percentage Of Carbon Dioxide (CO_2) Which Is Contained In The Flue Gases Indicates The Amount Of Excess Air Which Is Being Used (Fig. 416). Assuming that the flue gases contain no CO (carbon monoxide) a high percentage of CO_2(Sec. 483) indicates a small amount of excess air, and a low percentage of CO_2 indicates a large amount of excess air. The percentage of O_2 (oxygen, Sec. 475) would be a better indication of the quantity of excess air, but it is more difficult to determine than is the CO_2. The greater the value of the excess air which flows through the furnace, the greater will be the weight of the flue gases per pound of fuel burned, and (Sec. 484) the greater will be the quantity of heat which is lost by being carried out of the furnace by the flue gases. The general procedure to be followed to obtain a high CO_2 value and consequently a low percentage of excess air, is outlined in the note below.

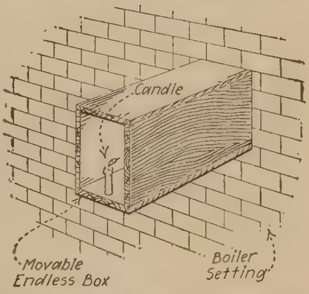


FIG. 421.—Lighted candle used for locating air leak into a boiler setting. The box (which is open at both ends) is used around the candle to protect it from side drafts.

NOTE.—THE GENERAL METHOD FOR OBTAINING A HIGH PERCENTAGE OF CO_2—12 to 15 per cent.—is as follows: With a lighted candle (Fig. 421), explore the entire outer surface of the boiler setting for leaks. Wherever there is a leak in the setting there will be a tendency to draw the candle flame into the setting. Test carefully at joints and where pipes and breechings enter. Using a sharpened wooden stick as the caulking tool, caulk all leaks with a thin mixture of fireclay and cotton waste. Do not use lime or cement mortar because it will fall out after drying. Then, adjust the thickness of the fire so that the highest percentage of CO_2 (usually 12 to 15 per cent.) is obtained with the smallest draft pressure over the fuel bed that will carry the load. This will have to be determined by a "cut and try" for each individual condition. The thickness of the fire can be measured by "calibrating" (Fig. 422) the fire hoe. This is done by placing marks on the hoe 1 in. apart with a pumice-stone pencil. The draft pressure over the fuel bed is measured with a draft gage (Sec. 676). The percentage of CO_2 is obtained by the flue-gas analyzer (Sec. 475). The fuel bed must be kept clean and free from holes. If the above procedure is judiciously followed, a high percentage of CO_2 can usually be obtained with practically no CO.

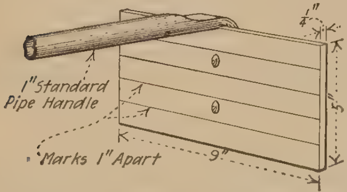


FIG. 422.—Calibrated fire hoe for determining the thickness of the fire.

494. If The Flue Gases Contain More Than A Trace Of CO (Carbon Monoxide) A Large Amount Of Heat Is Being Wasted Which Can Be Prevented. The *U. S. Geological Survey* found that by decreasing the percentage of CO from 0.7 per cent. to 0.3 per cent., the efficiency of combustion was increased from

57 to 65 per cent. That is, a 2 per cent. increase in the furnace efficiency resulted for every 0.1 per cent. decrease, by volume, of the CO in the chimney gases. This is about 4 times the theoretical amount which would be obtained by For. (334) of Sec. 483. The reason for this excess above the theoretical loss (Sec. 483) is that the presence of an appreciable amount of CO in the flue gases is usually accompanied by unburned hydrocarbons and hydrogen. When the air supply is insufficient (Sec. 472), or if sufficient and not properly distributed, the combustion of the carbon will be incomplete (Sec. 466) and CO will be formed. See note below.

NOTE.—THE PERCENTAGE, BY VOLUME, OF THE CO (CARBON MONOXIDE) WILL GENERALLY BE VERY SMALL, EVEN WITH A SMALL AMOUNT OF EXCESS AIR, IF A HIGH PERCENTAGE OF CO_2 (CARBON DIOXIDE) HAS BEEN OBTAINED as explained in the preceding section. However, large amounts of CO may exist with almost any amount of CO_2. Thus, if the fire is thick and dirty in one part of the furnace, the coal in this portion will not receive sufficient oxygen for complete combustion. Consequently, a large quantity of CO will result. If, at the same time, there is a thin place or a hole in another part of the fire, a large amount of air will rush through, and the CO_2 will be small. Do not attempt to secure a high percentage volume of CO_2 by cutting down the air supply only. If this is done, it will usually result in the formation of CO

QUESTIONS ON DIVISION 14

1. Define combustion.

2. What are the principal substances which are contained in coal?

3. From what source is the oxygen for the combustion of coal in a furnace usually obtained?

4. What are the principal constituents of air? In what proportions do these constituents exist by volume? By weight?

5. Explain what occurs when 1 lb. of carbon is completely burned in air?

6. Explain with a diagram the chemical reaction which occurs to some extent in a furnace when carbon dioxide is reduced to carbon monoxide.

7. Explain what occurs when 1 lb. of carbon is incompletely burned to carbon monoxide.

8. Why must the quantity of air which is supplied to a furnace be greater than that which is theoretically necessary for the combustion?

9. What are the principal products of combustion which are formed when coal is burned in air?

10. What is meant by flue-gas analysis? Describe, briefly, a commonly employed method of making a flue-gas analysis.

11. Why cannot the sum of the percentages, by volume, of the oxygen, the carbon dioxide, and ½ the carbon monoxide be equal to the percentage, by volume, of the oxygen in the air which was supplied to the furnace?

12. Name and explain 7 different wyas in which heat from a boiler furnace is lost?

13. Which of the avenues of heat loss from a boiler furnace may be practically controlled by the fireman?

14. What is meant by "rate of combustion?" For a given grate burning a given coal, what things govern the rate of combustion?

15. In general, what does a high percentage, by volume, of CO_2 in the flue gases indicate?

16. Explain the general methods for obtaining a high percentage of CO_2 and a low percentage of CO.

17. Why does CO in the flue gas indicate a low efficiency of combustion?

PROBLEMS ON DIVISION 14

1. The percentages, by volume, of a flue-gas analysis are reported as follows: Carbon dioxide, 8 per cent.; oxygen, 7 per cent.; carbon monoxide 1 per cent.; nitrogen, 84 per cent. What is the weight of air which is being supplied per pound of fuel if 0.8 lb. of carbon is burned in the furnace for each pound of fuel which is fired?

2. What is the percentage of excess air which is being supplied in Prob. 1?

3. What is the weight of the dry flue gases formed per pound of fuel burned in Prob. 1?

4. If 0.8 lb. of carbon is burned in the furnace for each pound of fuel fired, what is the heat loss per pound of fuel due to incomplete combustion?

DIVISION 15

STEAM POWER PLANTS

495. The Function Of A Steam Power Plant (Fig. 423) is to convert into mechanical work the chemical energy (Sec. 28) which nature has stored in the fuel. In performing this function, the chemical energy—or a part of it, at least—which is contained in the fuel and in the oxygen of the air, is in the boiler furnace, transformed into and given up as heat energy, by combustion (Div. 14). Much of the heat energy thus liberated, is transferred to water in the boiler; this heat added to the water vaporizes the water into steam, in which most of the heat remains stored for transmission. This heat stored in the steam is then transmitted in pipes to some mechanical device (engine) which is so designed that a part of the heat energy in the steam is by the heat enigne transformed into mechanical work.

NOTE.—THE PURPOSE OF THIS DIVISION is to describe briefly the fundamental function and the operation of some of the more essential components of the modern steam power plant. For a more detailed treatment of these various elements, the reader is referred to the following books by the author: "Steam Boilers," "Steam-engine Principles And Practice," "Steam-turbine Principles And Practice" and "Steam Power Plant Auxiliaries And Accessories."

496. The Essential Parts Of A Steam Power Plant (Fig. 423) are: (1) *The boiler furnace, F.* (2) *The boiler, B.* (3) *The steam piping, P.* (4) *The prime mover, E.* The functions of each of these parts are described in the notes below and the parts themselves are further discussed in following sections.

NOTE.—THE BOILER FURNACE AND THE BOILER are frequently so constructed that a definite and rigid distinction cannot always be made as to just what part constitutes the boiler and what part constitutes the furnace. *The boiler furnace* (*F*, Fig. 423) generally consists of some device, such as a grate (under *F* in Fig. 423) or burner (Fig. 429) for

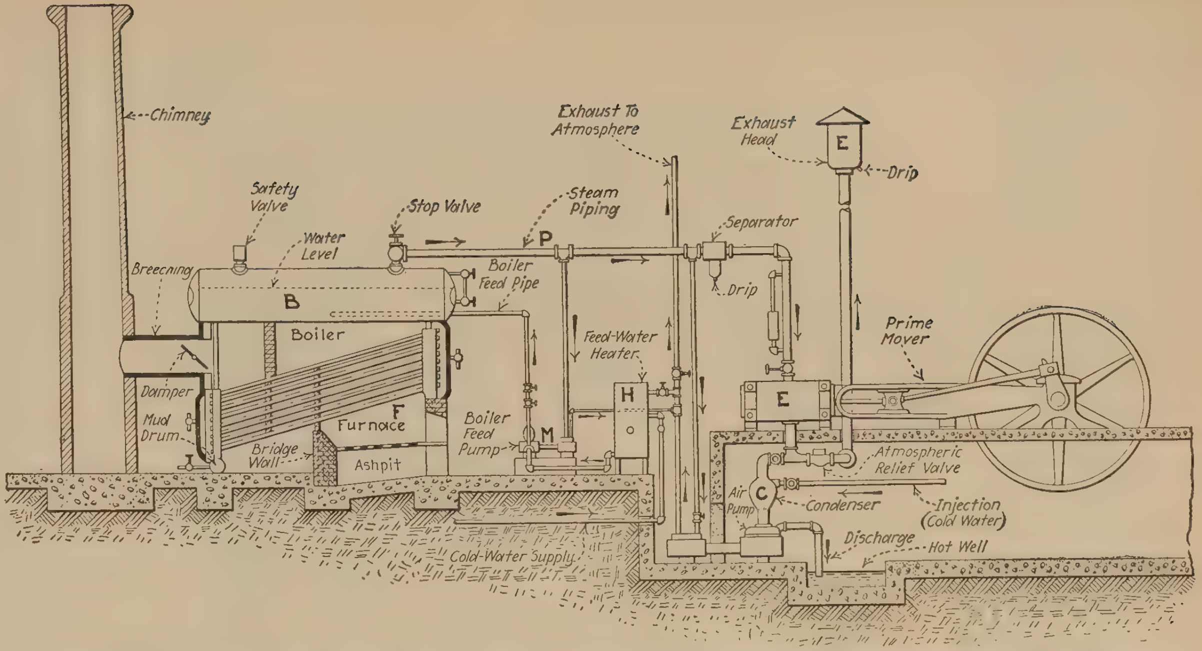


FIG. 423.—An elementary steam power plant consisting principally of a furnace, boiler, piping, steam engine, and condenser. If the condenser, *C*, fails then the atmospheric relief valve operates automatically and causes the engine to operate non-condensing, exhausting to the atmosphere through *E*.

bringing the air which is necessary for combustion (Sec. 472) into intimate contact with the fuel, and a space, or *combustion chamber*, usually enclosed by firebrick or metal, wherein the combustion is completed and the hot products of combustion (Sec. 463) transmit a part of the heat which they contain to the boiler. The *boiler* is a closed vessel in which, by the absorption of the heat of combustion of the fuel, water is boiled and thereby converted into steam. The heat of combustion of the fuel is transmitted to the walls of the boiler by radiation (Sec. 138), conduction (Sec. 111) and convection (Sec. 137). The heat is transmitted by conduction through the walls of the boiler to the water which is contained within the boiler. By the addition of a sufficient quantity of heat to the water, it is caused to boil (Sec. 313) and form steam. Thus, a part of the chemical energy in the fuel is transformed into heat energy and stored up in the steam as such. Practically any liquid could be used in the boiler as the storage and transmitting medium for the heat energy. However, due to the almost unlimited supply of it and also to certain of its inherent characteristics, water—or water vapor which is steam—is, where the combustion of the fuel does not occur within the engine cylinder, always used as the medium in which the heat of com-

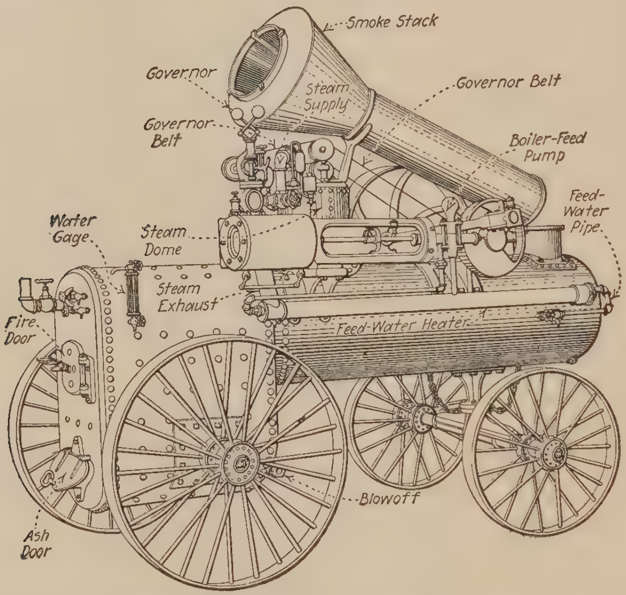


Fig. 424.—A complete portable non-condensing steam power plant. A self-contained hoisting-engine-and-boiler outfit is another example of a complete portable steam power plant.

bustion is stored for transmission from the furnace to the prime mover. See Sec. 391 for the reasons why water is the best medium for this purpose.

NOTE.—THE FUNCTION OF THE STEAM PIPING (*P*, Fig. 423) is to conduct the heat in the steam from the boiler to the prime mover. If the prime mover is mounted on the boiler (as it is in the locomobile and in portable power plants, Fig. 424, of certain types), the steam piping can be omitted. However, practical considerations generally prohibit such an arrangement for plants of medium or large capacity. The pipes which conduct the steam from the boiler to the prime mover are generally covered with some heat insulating material which offers great resistance (Sec. 114) to heat flow. Thus, the loss of heat from the steam, between the boiler and the prime mover, is minimized; see Fig. 425.

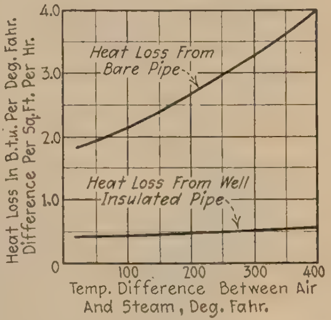


FIG. 425.—Heat loss from steam pipes.

NOTE.—THE FUNCTION OF THE PRIME MOVER OF A STEAM POWER PLANT is to convert into mechanical work the maximum possible amount of the heat energy which is delivered to it in the steam. The prime mover in a steam power plant is either a reciprocating steam engine (Sec. 502) or a steam turbine (Sec. 505). The engine or turbine drives mechanically an electric generator, a line shaft, or some other device which will transmit energy or useful work.

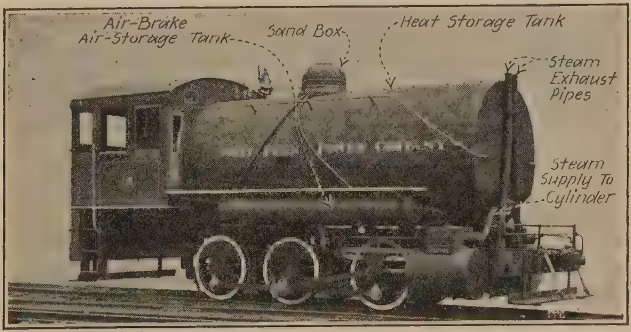


FIG. 426.—Fireless locomotive. Note the absence of the smoke stack. (*H. K. Porter Co., Pittsburgh, Pa.*)

NOTE.—THE FIRELESS LOCOMOTIVE (Fig. 426) is not a complete steam power plant because its heat energy does not come to it in a fuel—no combustion occurs in it. But it does provide an interesting example of the conversion of heat energy in steam into mechanical work. Its operation is as follows: The locomotive carries a storage tank, somewhat similar to a boiler, which has a capacity of about 760 cu. ft. This tank is first about 4/5 filled with water. Then the tank is connected to a stationary steam boiler wherein the steam pressure is about 350 lb. per sq. in. The tank and the boiler are permitted to remain connected until no more steam will flow into the tank. Then the connection is broken. The storage tank, which is well insulated against heat loss, now contains water and steam at a pressure of about 350 lb. per sq. in. gage, which is at a temperature of about 437° F. (see Steam Table 394). As the steam is taken from the storage tank to drive the locomotive, the pressure in the tank decreases, whereupon more steam is formed due to the heat stored in the water. When the pressure within the tank drops to about 20 or 30 lb. per sq. in., the tank must be recharged. Under normal operation, the locomotive will operate from 2 to 10 hr. with one charge. Its principal use is in industrial-plant service where electric or other steam locomotives would be hazardous.

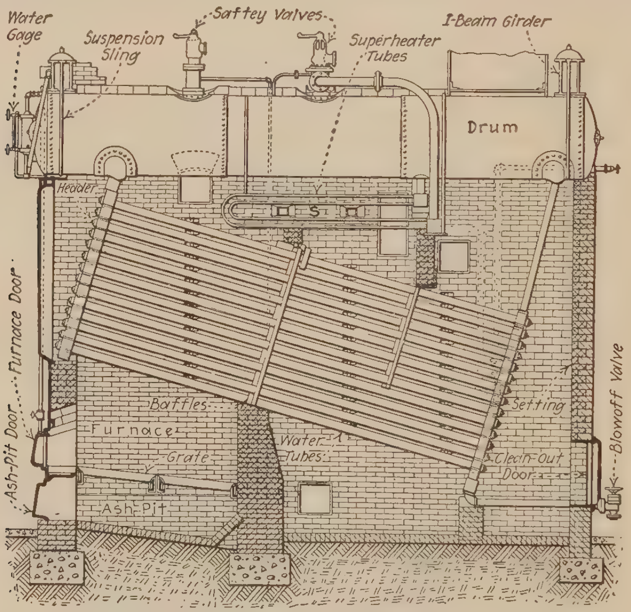


Fig. 427.—A hand-fired coal-burning water-tube boiler furnace (*Babcock & Wilcox Co*).

497. The Principal Types Of Boiler Furnaces are: (1) *Hand-fired furnace*, Fig. 427. (2) *Stoker-fired furnace*, Fig. 428. (3) *Oil-burning furnace*, Fig. 429. (4) *Gas-burning furnace*, Fig.

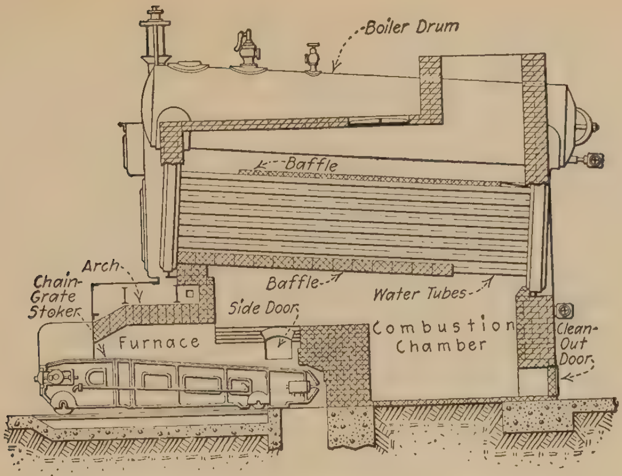


FIG. 428.—A stoker-fired (chain-grate stoker) boiler furnace.

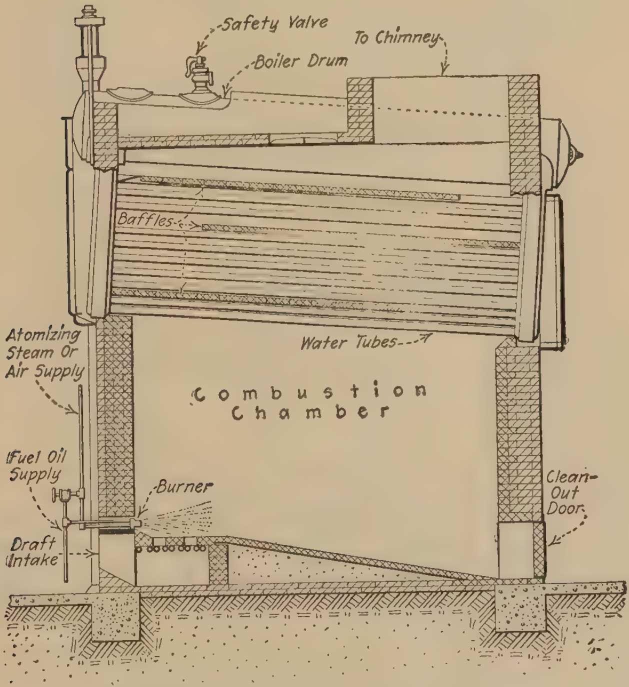


FIG. 429.—A typical fuel-oil-burning furnace.

430. (5) *Powdered-coal-burning furnace*, Fig. 431. The hand-fired (Fig. 427) and the stoker-fired furnaces (Fig. 428) are used, respectively, in small and in large capacity installations for burning coal as received from the mine. A powdered-coal-burning furnace is used to burn coal which has been mechanically pulverized to a fine dust; powdered coal is now used only (but with great economy) in large plants. The fuel which is used in an oil-burning furnace is generally fuel oil. Gas-burning furnaces burn either natural or some artificial gas. Furnaces of each of these different types are made in a number of different forms, depending upon the kind of fuel which is to be used, upon the type of stoker, if any, upon the kind of boiler (Sec. 498) with which they are to be used, and upon the opinions of the designer.

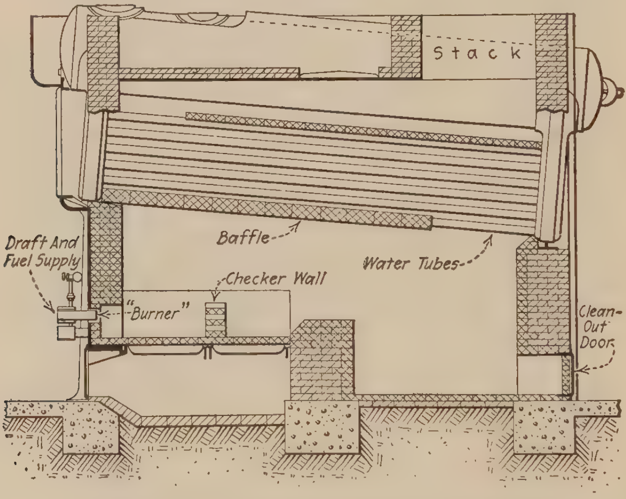


Fig. 430.—A boiler furnace for burning natural gas.

498. Steam-power-plant Boilers May Be Classified according to a number of different schemes (see the author's "Steam Boilers"). However, practically all modern boilers are either: (1) *Fire-tube boilers*, Fig. 432, wherein the drum contains a number of tubes which are surrounded by water, and through which the high-temperature gaseous products of combustion are passed. (2) *Water-tube boilers*, Figs. 427, 428, and 431.

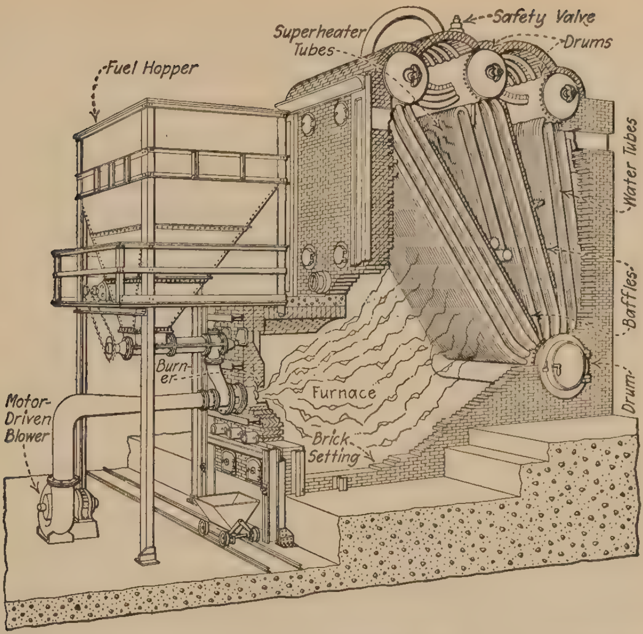


FIG. 431.—A powdered-coal-burning furnace, Sterling Boiler. (Fuller-Lehigh Company pulverized-coal equipment.)

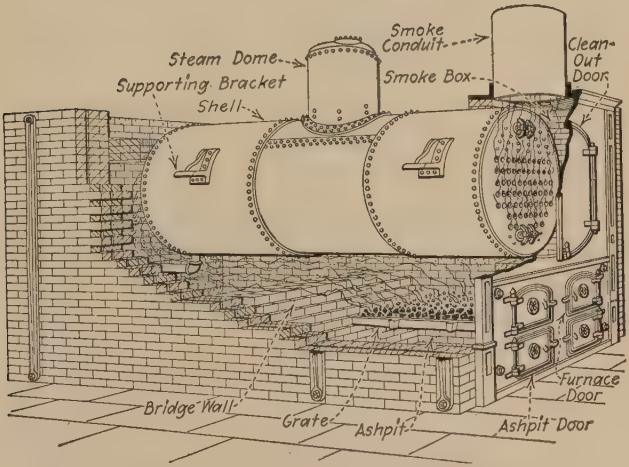


FIG. 432.—A fire-tube boiler—return-tubular.

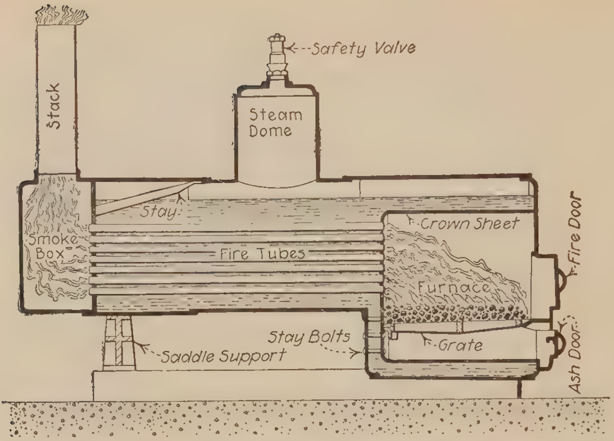


FIG. 433.—A locomotive-type boiler—internally-fired, fire-tube.

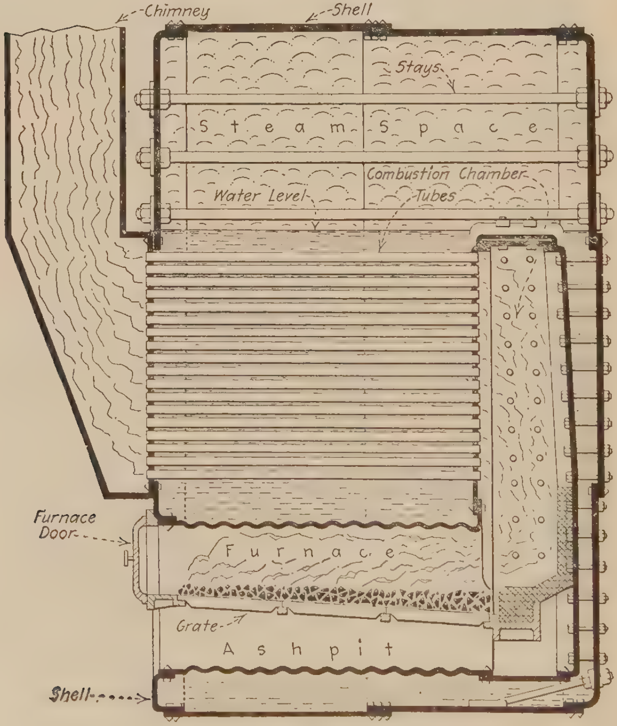


FIG. 434.—A Scotch-marine steam boiler—internally-fired, fire-tube.

wherein a number of tubes are connected to one or more drums and the high-temperature gaseous products of combustion are passed over the tubes which are filled with water. (3) *A combination of fire tubes and water tubes.* The reason for the tubes, whether fire tubes or water tubes, is to increase the area of the boiler surface which is exposed to the hot gases. By thus increasing the area (Sec. 115) which is in contact with the hot gases, the heat transfer from the gaseous products of combustion to the water within the boiler is materially increased. Fire-tube boilers are built in three principal types as described in the following note.

Note.—The Principal Types Of Fire-tube Boilers are: (1) *The return-tubular boiler,* Fig. 432. (2) *The locomotive-type boiler,* Fig. 433. (3) *The Scotch-marine boiler,* Fig. 434. *An externally-fired boiler* is one which has a separate furnace built outside of the boiler shell. *An internally-fired boiler* is one wherein the furnace is located within the boiler and forms an integral part with it. Practically all water tube boilers (Figs. 427, 428, and 431) are of the externally-fired type. The return-tubular boiler (Fig. 432) is an externally-fired fire-tube boiler. The locomotive-type boiler (Fig. 433) and the Scotch-marine boiler (Fig. 434) are internally-fired fire-tube boilers In general, the applications of the boilers of the various types mentioned above are about as follows: (1) *Return-tubular and water-tube boilers for medium-capacity stationary installations;* only water-tube boilers are used for large-capacity installations. (2) *The locomotive-type boiler for portable and small-capacity stationary installations.* (3) *The Scotch-marine boiler for land and marine service where the available boiler space is small.*

499. The Efficiency Of A Boiler And Furnace (and grate if the furnace has one) is the ratio between the quantity of heat which is absorbed by the water and steam in the boiler and the quantity of heat which should have been liberated by the complete combustion of the fuel which is fired. This may be written as a formula thus:

$$\mathbf{E} = \frac{\mathbf{Q}_B}{\mathbf{H}} \qquad \text{(decimal)} \tag{342}$$

Wherein: $\mathbf{E}$ = the efficiency of the boiler and furnace (and grate, if any) expressed decimally. $\mathbf{Q}_B$ = heat, in British thermal units, which is absorbed by the boiler per pound of fuel fired; $\mathbf{Q}_B$ is computed from the data obtained in an evaporation test. $\mathbf{H}$ = the heating value (Sec. 452) in British thermal units per pound of *fuel as fired;* **H** is determined (Div. 13) by a calorimeter test of the fuel or (Sec. 469) from the results of the ultimate analysis of the fuel.

EXAMPLE.—During an evaporation test it was found that a certain boiler absorbed 9,346 B.t.u. for each pound of coal which was fired. The heating value of the coal, as fired, was 12,600 B.t.u. per lb. What was the efficiency of the boiler, furnace, and grate? SOLUTION.—By For. (342), *the efficiency of the boiler, furnace, and grate,* $\mathbf{E} = \mathbf{Q}_B/\mathbf{H} = 9{,}346 \div 12{,}600 = 0.741$, or 74.1 *per cent.*

500. Steam Boilers Are Rated In Boiler Horsepower.—A boiler horsepower, is equivalent to the evaporation of 34.5 lb. of water per hour, at a temperature of 212° F. and atmospheric pressure, to steam at the same temperature and pressure. This is equivalent to 33,479 B.t.u. per hr. This unit—the boiler horsepower—is an arbitrary one. It has no definite mathematical relation to the horsepower unit which is used for expressing the rate of doing work (Sec. 36). Inasmuch as the rate of evaporation of a boiler depends on the setting, the fuel, and the method of firing, boiler manufacturers actually rate a boiler on the basis of its heating surface. A modern boiler will, if operated under ordinary conditions as to setting, fuel, and firing, develop about 1 boiler hp. (one boiler horsepower) for each 10 sq. ft. of heating surface. Hence, the manufacturers rate their boilers on the basis of 1 boiler hp. for each 10 sq. ft. of water heating surface that the boilers contain.

EXAMPLE.—A boiler which has 2,000 sq. ft. of heating surface will be rated as a: 2,000 ÷ 10 = 200 *boiler hp.* boiler. This boiler will, under average conditions, readily develop 200 hp. But by forcing—assuming sufficiently large grate area—all boilers may develop 50 per cent. more than their rated horsepower. Good water-tube boilers may develop continuously 300 per cent. rating and on short duration peak loads 600 per cent. rating.

501. The Prime Mover Of A Steam Power Plant is the machine—heat engine—wherein a portion of the heat energy of the steam is converted into work. This machine is usually either a *reciprocating steam engine* or a *steam turbine.* For a detailed description of many of the several different types of steam engines and steam turbines see the author's

"Steam-engine Principles And Practice" and "Steam-turbine Principles And Practice." A brief discussion of the principles of operation of the steam engine and the steam turbine are given herein in Secs. 502 and 506 respectively.

Note.—As To The Applications Of Engines And Turbines, turbines will prove the most economical in practically all large-capacity installations. In medium- or small-capacity installations, either engines or turbines may prove the most economical, depending upon the conditions. Turbines are inherently high-speed constant-speed machines, which may render their use impracticable for certain applications for which they otherwise might be the most economical. Turbines have no heavy reciprocating parts as have reciprocating steam engines. For equal power output the space occupied by a steam turbine is much less than that occupied by a steam engine. Turbines are considerably lower in first cost than engines of equal power; this is because of the higher speeds and simpler construction of the turbines.

502. The Principle Of Operation Of A Simple Reciprocating Steam Engine (Fig. 435) may be understood from the following:

Explanation.—As shown in Fig. 435, the piston P is just a little beyond dead center so that if a sufficient force in a right-hand direction is exerted upon the piston, it will move in that direction. At this position of the piston, the slide-valve, D, is in a position such that the port of the steam-passage, H, is slightly open. Live steam (which is at a considerable pressure) from the boiler flows through the live-steam pipe, S, into the steam chest, M, and fills M. From the steam chest, the steam passes through the steam passage, H, and into the cylinder on the left-hand side of the piston, P. The pressure which the steam exerts on the piston forces the piston to the right. This rotates the main shaft.

As the piston is thus forced to the right, steam continues to flow through H into the cylinder until the valve, D, which is actuated by the shaft through the eccentric rod, J, and the valve stem, L, in moving to the left closes the port to the steam passage, H. This is called *the point of cut-off* (C, Fig. 436). That is, the steam supply to the cylinder is cut off. The steam which is thereby entrapped in the cylinder is, at the point of cut-off, at a comparatively high temperature and pressure. Consequently, the steam continues to exert a force on the piston to the right. As the piston continues to be forced to the right by the expanding steam, the steam space in the cylinder on the left of the piston increases. That is, the steam expands behind the piston and in so doing continues to exert a pressure on it.

While the piston has been forced to the right as explained above, the valve D has been moved to the left, so that just a little before the piston reaches its extreme right-hand position, the D-shaped slide-valve has

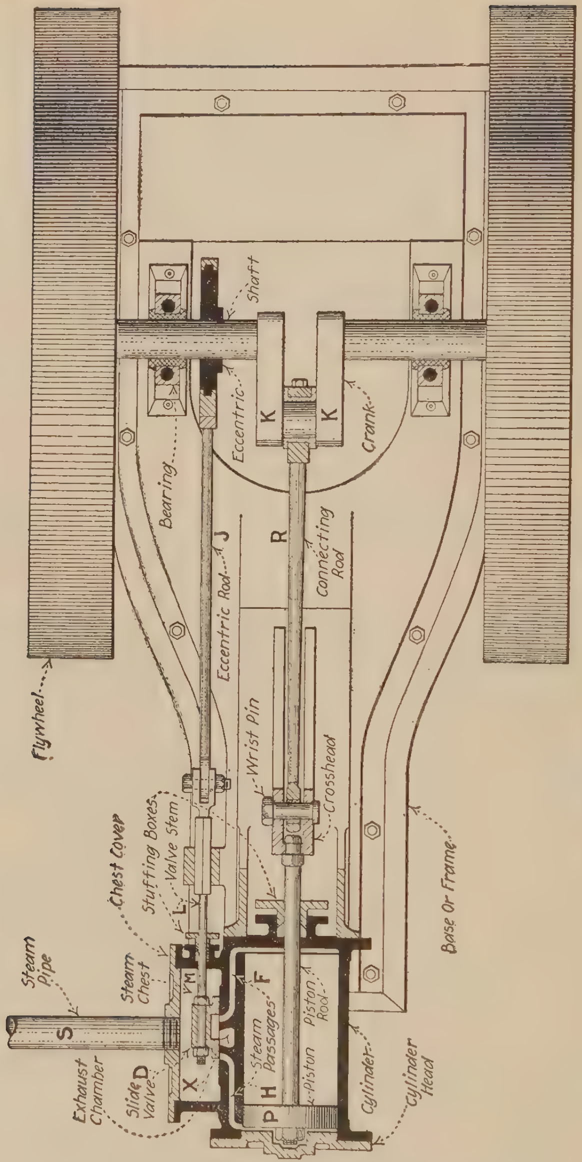


FIG. 435.—Sectional view of a simple D-slide-valve steam engine.

uncovered the port of the steam passage, *H*. But at this position the passage, *H*, instead of opening into the steam chest, now opens into the exhaust chamber *X*. The point at which the valve opens (*R*, Fig. 436) the steam passage to the exhaust chamber is called the *point of release.* The exhaust chamber connects to some region, such as the atmosphere or a condenser, wherein the pressure is lower than that of the steam in the cylinder at the point of release. Thus, when the steam passage *H* opens to the exhaust chamber *X*, the steam starts to flow out of the cylinder.

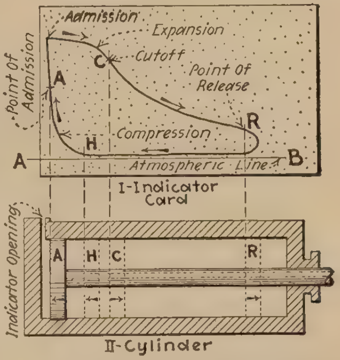


Fig. 436.—Indicator diagram of a steam engine showing position of piston when the various events of the cycle occur. The "Line Of Atmospheric Pressure" is made with the valve between the indicator and the engine cylinder closed—no steam in the indicator.

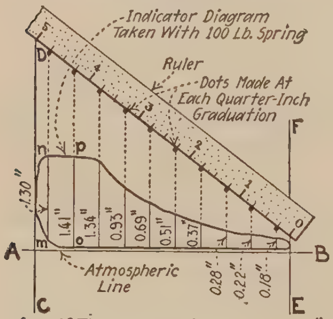
In a double-acting engine such as shown in Fig. 435, a short time after the steam passage *H* has opened to the exhaust, the slide valve uncovers the port of the steam passage, *F*, and steam begins to flow into the cylinder on the right-hand side of the piston. This forces the piston to the left in a manner similar to that described above.

As the piston is now thus forced to the left, it pushes the steam which is on the left-hand side of it out of the cylinder through *H* and the exhaust chamber, *X*. While the piston is now moving to the left, the slide-valve, *D*, moves to the right so that when the piston has completed about ¾ of its stroke (*H*, Fig. 436) the steam passage *H* is closed to the exhaust chamber. Then, when the piston travels a little farther to the left (*A*, Fig. 436), the slide valve is shifted a little farther to the right and the steam passage, *H*, is opened to the steam chest, *M*, and steam is now admitted to the left-hand end cylinder. This is called the *point of admission.*

The kinetic energy which has been stored in the moving flywheel will carry the piston over its dead center so that the steam which is now being admitted to the left of *P* begins another cycle of operation. As the engine continues to operate steam is thus alternately admitted to and exhausted from both sides of the piston. The reciprocating motion of the piston is transformed into rotary motion of the shaft by the connecting rod *R* (Fig. 435) and the crank, *K*.

503. A Steam-engine Indicator Diagram (Fig. 436) is a graph of the pressure variation within one end the cylinder of an engine while the piston is being forced from one end of the cylinder and back; such a graph is plotted by an indicator (Sec. 685). The net area included by a steam-engine indicator diagram is proportional to the work (Sec. 262) which was done on one side of the engine piston during the power stroke and the return stroke, when the diagram was taken. The average height between the upper and lower lines of the diagram is proportional to the *mean effective pressure* on the piston. The mean effective pressure may be determined from an indicator diagram by a planimeter, or as explained below, by the method of ordinates.

EXPLANATION.—THE MEAN EFFECTIVE PRESSURE MAY BE DETERMINED FROM AN INDICATOR DIAGRAM BY THE METHOD OF ORDINATES (Fig. 437) as follows: Draw two lines, *CD* and *EF*, perpendicular to the atmospheric line *AB* so that each line is tangent to the indicator diagram at one of its ends. Then take a ruler and place the zero graduation at any point on one of the lines, *EF*, and the 5-in. graduation on the other line, *CD*. With a sharp-pointed pencil make a dot (Fig. 437) on the indicator card at each quarter-inch graduation; that is, at the ¼-in., the ¾-in., the 1¼-in., the 1¾-in., graduations, etc. Remove the ruler, and through each dot thus made, draw a pencil line (shown dotted in the illustration) through the indicator diagram (as *mn*, *op*, etc., Fig. 437) perpendicular to the atmospheric line *AB*. Then measure the length in inches, of that portion of each line which is within the indicator diagram. Add together the lengths, in inches, of all of the lines and divide the sum by the number of lines, which is 10. Multiply this quotient by the scale of the indicator spring. The result is the mean effective pressure in pounds per square inch. See the following example.



Sum Of The Lengths Of The Lines=7.23"
Average Height Of Diagram= 7.23"÷10=0.723"
Mean Effective Pressure= 0.723 x 100=72.3 Lb. Per Sq. In.

FIG. 437.—Determining the mean effective pressure from an indicator diagram by the method of ordinates.

EXAMPLE.—The scale of the spring, which was used in taking the indicator diagram shown in Fig. 437, was 100. What was the mean effective pressure? SOLUTION.—The vertical lines within the indicator diagram (Fig. 437) were drawn as explained above. The length, in inches, of each is as shown. *The sum of the lengths* = 1.30 + 1.41 + 1.34 + 0.93 + 0.69 + 0.51 + 0.37 + 0.28 + 0.22 + 0.18 = 7.23 *in.* The *sum of the lengths divided by the number of lines* = 7.23 ÷ 10 = 0.723 *in.*, which is the average height of the diagram. Since the scale of the spring is 100, *the mean effective pressure* = 0.723 × 100 = 72.3 *lb. per sq. in.*

504. The Power Which Is Developed By The Steam Within The Engine Cylinder May Be Determined as explained below. This power, when expressed in horsepower, is called the *indicated horsepower.* It may be determined by the following formula:

$$\mathbf{P} = \frac{PLAN}{33{,}000} \qquad \text{(indicated horsepower)} \tag{343}$$

Wherein: $\mathbf{P}$ = the indicated horsepower which is developed in that end of the cylinder for which the indicator diagram is taken. P = the mean effective pressure, in pounds per square inch, as determined from the indicator diagram (Sec. 503). L = the length of stroke, in feet. A = the area of the piston, minus the area of the piston rod, if the piston rod extends through the head of that end of the cylinder from which the indicator card is taken, in square inches. N = the number of revolutions per minute of the main shaft. If the engine has more than one working cylinder end, the indicated horsepower is determined as explained above for each end. Then, the total indicated horsepower of the engine is the sum of the indicated horsepower developed in all of the working cylinder ends.

EXAMPLE.—The indicator card shown in Fig. 437 was taken from the head-end of a steam engine cylinder. That is, the piston rod did not extend through the cylinder-end from which the indicator card was taken. The length of stroke was 2 ft. The diameter of the piston was 20 in. The engine was running at 125 r.p.m. What was the horsepower which was being developed in that end of the cylinder? SOLUTION.—By the solution to the problem under Sec. 503 *the mean effective pressure* = 72.3 lb. per sq. in. *The area of the piston* = $3.14 \times 20 \times 20 \div 4 = 314$ *sq. in.* By For. (343), *the indicated horsepower for this end of the cylinder,* $\mathbf{P} = PLAN/33{,}000 = (72.3 \times 2 \times 314 \times 125) \div 33{,}000 = 172$ *hp.* If the engine is a *double-acting* one, as is that of Fig. 435, and the power developed by the crank end is the same as that for the head-end—which it probably would be approximately—then the *total power developed by the engine* = $2 \times 172 = 344$ *hp.*

505. The Steam Turbine (Fig. 438) is, when it is operated condensing, a very efficient device for transforming into mechanical work the heat energy which is contained in the steam. Steam turbines are manufactured in capacities ranging from ½ to 30,000 kw. Their principal uses are as prime movers for driving electric generators and for driving auxiliaries (Sec. 509) in steam power plants, and for driving centrifugal pumps in pumping stations. In a steam-turbine power plant, the prime mover is usually operated condensing (Sec. 513) and the turbines which drive the auxiliaries are operated non-condensing. Then, the exhaust steam from the turbines which drive the auxiliaries is used for heating the feed water (Sec. 518). Steam turbines are inherently high-speed machines, the usual operating speeds being from 1,500 to 4,000 r.p.m.

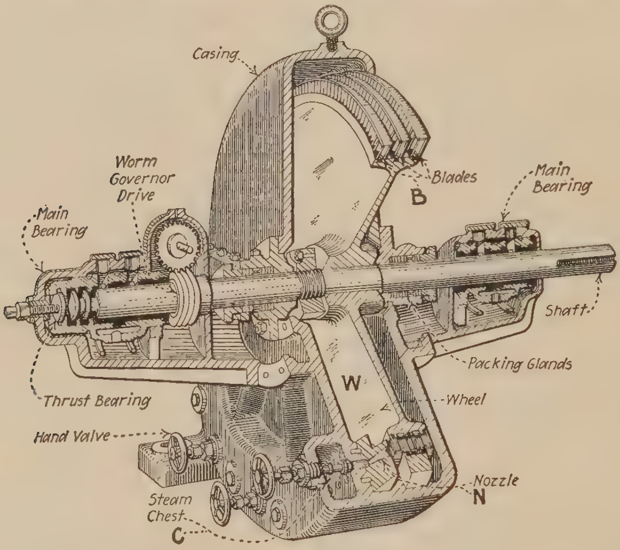


Fig. 438.—An Alberger-Curtis impulse-type steam turbine having three rows of moving blades.

506. Steam Turbines Are Of Two Principal Types: (1) *The impulse turbine.* (2) *The reaction turbine.* Turbines are also frequently made wherein both of the above types are combined in one machine. The principles of operation of turbines of each of these two types are briefly explained in the following notes.

Note.—The Principle Of Operating A Steam Turbine Of The Impulse Type (Fig. 439) is as follows: Steam which is at a high temperature and pressure flows from the steam chest, *C*, Fig. 438, through the nozzle, *N* (Figs. 438 and 440). As the steam issues from the nozzles. *N*, at an extremely high velocity it strikes the blades, *B*, and causes the

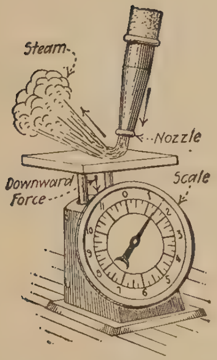


FIG. 439.—Force due to impulse of steam on scales.

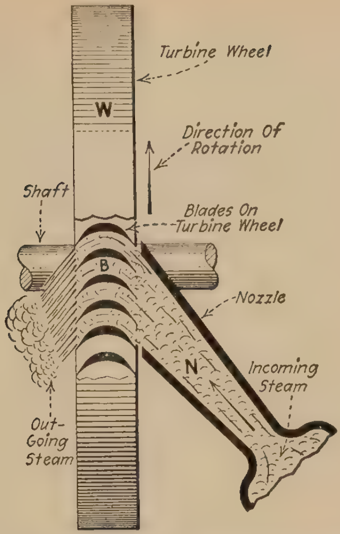


FIG. 440.—Illustrating operation of an impulse steam turbine. The impact of the high-velocity steam issuing from the nozzle, *N*, on the blades, *B*, causes the wheel to rotate.

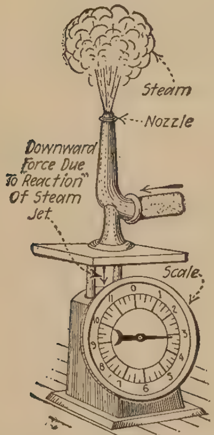

Steam
Nozzle
Downward Force Due To Reaction Of Steam Jet
Scale

FIG. 441.—Force due to reaction of steam leaving nozzle. After the steam is turned on the scales register the reactive force of the steam jet in addition to weight of nozzle.

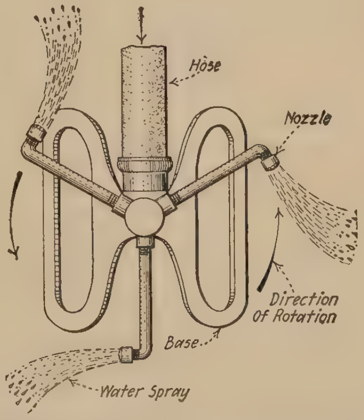


FIG. 442.—Reaction of water leaving nozzles in whirling lawn sprinkler causes it to rotate.

wheel, *W*, to rotate. The diverging nozzle, *N*, is so designed that the steam in passing through it undergoes practically frictionless adiabatic (isentropic) expansion (Sec. 385). During this expansion, the heat energy of the steam is transformed into kinetic energy (Sec. 385). Thus, the steam issues from the nozzle at a high velocity, usually from about 2,900 to 4,000 ft. per sec. In the impact of this high-velocity steam on the turbine blades, a large part of the kinetic energy is transformed into mechanical work of turning the wheel. After the steam leaves the wheel it is ordinarily exhausted from the turbine casing into the atmosphere, into a feed-water heater (Sec. 518), into a building or industrial-process heating system (Div. 17), or into a condenser (Sec. 513).

Note.—In Turbines Of The Reaction Type, the expansion of the steam occurs largely in moving nozzles (Figs. 441 and 442). That is, the moving blades on the turbine rotor or wheel, are so designed that the steam expands in passing through them. As the steam expands in these moving nozzles the heat energy is transformed into kinetic energy in essentially the same manner as was described above for the impulse turbine. As the steam issues from the moving nozzle at the high velocity thus acquired by the expansion, it "kicks back," or produces a reactive force on the moving nozzle of the wheel and causes it to rotate. This "reaction" occurs only when the steam leaves the nozzle with a velocity higher than that with which it approached the nozzle.

507. The Efficiency Of A Steam Prime Mover (Sec. 501) as a device for converting into mechanical work at the shaft the heat energy which is in the steam that is supplied to it, is called the *thermal brake efficiency* or *overall efficiency*, Sec. 436. It may be computed by the following formula:

$$(344) \qquad \mathbf{E} = \frac{2{,}545 \times \mathbf{P}_B}{\mathbf{W}_S(\mathbf{H} - \mathbf{h})} \qquad \text{(decimal)}$$

Wherein: **E** = the thermal brake efficiency, expressed as a decimal. $\mathbf{P}_B$ = the power, in horsepower, delivered by the shaft; that is, it is the brake horsepower as is determined, usually, by a brake on the shaft or with an electric generator which is driven by the shaft. $\mathbf{W}_S$ = the rate of steam consumption of the prime mover in pounds per hour (see note below). **H** = total heat, in British thermal units per pound, of the steam (Sec. 365) at the throttle. **h** = the heat of the liquid, in British thermal units per pound (Sec. 363) at the exhaust temperature.

Note.—Thermal Brake Efficiencies of *reciprocating steam engines* vary from about 5 per cent. for small-capacity, non-condensing, simple engines, to about 25 per cent. for large-capacity, condensing, triple-expansion engines. For *steam turbines* the thermal brake efficiencies vary from about 7 per cent. in small-capacity, non-condensing turbines, to about 28 per cent. in large-capacity condensing turbines.

Note.—The Water Rate Of A Steam Prime Mover May Be Defined as the number of pounds of steam which is required to develop one unit of energy. The unit of energy, which is usually specified in a manufacturer's water-rate guarantee for the prime mover, is either the indicated horsepower-hour, brake horsepower-hour, or the kilowatt-hour. The manufacturer's water-rate guarantee is always based upon the specified initial and exhaust steam conditions, the load, and the speed in revolutions per minute. The water rate of a steam prime mover is, when stated in conjunction with the initial and exhaust steam conditions, an indication of the efficiency of operation. But, the water rate is a rather meaningless value unless the steam conditions under which it was obtained are given. *The water rates of reciprocating steam engines* vary from about 12 lb. per b.hp.-hr. for large-capacity compound condensing engines to 45 or 50 lb. per b.hp.-hr. for small-capacity simple non-condensing engines. *The water rates of steam turbines* vary from about 7.5 lb. per b.hp.-hr. for large-capacity condensing turbines to over 40 lb. per b.hp.-hr. for small-capacity non-condensing turbines.

508. The Commercial Rating Of Steam Prime Movers Is Usually Based On The Power Output Somewhere Near The Most Efficient Load.—If the prime mover is direct connected to an electric generator, it is usually rated in the kilowatt output measured at the generator terminals. If the prime mover is not direct connected to an electric generator, it is ordinarily rated in brake horsepower measured at the main shaft. Such ratings are usually contingent upon a certain speed in revolutions per minute, and upon certain initial and final steam conditions. Practically all steam prime movers are capable of carrying a load which is at least 25 per cent. greater than the full-load name-plate rating.

509. The Principal Auxiliaries With Which Steam Power Plants Are Frequently Provided are: (1) *Boiler-feeding apparatus* (*M*, Fig. 423), Secs. 510 to 512. (2) *Condensers* (*C*, Fig. 423), Sec. 513 to 515. (3) *Feed-water heaters* (*H*, Fig. 423) Secs. 516 to 522. (4) *Superheaters*, Sec. 523. (5) *Artificial draft apparatus*, Sec. 524. The purpose of such auxiliaries (with the exception of the boiler-feeding apparatus) is to improve the economy of the plant. Whether or not the economy of the plant will be improved by an auxiliary will depend upon the size of the plant and upon local conditions and must be determined for each individual plant. Refinements are not ordinarily justified in small plants. The remainder of this division contains a brief description of the function and of the operation of the principal types of the more important steam-power-plant auxiliaries. For a detailed treatment of these devices, see the author's "Steam Power Plant Auxiliaries and Accessories."

510. The Two Principal Types Of Boiler-feeding Apparatus are: (1) *Injectors*, Sec. 511. (2) *Pumps*, Sec. 512. As the water in the boiler is evaporated into steam and as the steam is used by the prime mover, more water must be fed to the boiler. Since the steam in the boiler is at a relatively high pressure (say, 60 to 250 lb. per sq. in.) some device must be used to force the feed water into the boiler against this pressure. Sometimes, the water is fed to the boiler by a gravity-operated trap; see the author's "Steam Power Plant Auxiliaries and Accessories." In stationary steam power plants, injectors are generally used only for stand-by service. Pumps are the most important boiler-feeding apparatus.

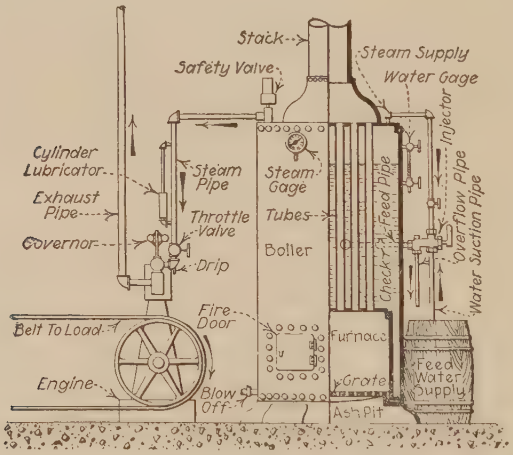


Fig. 443.—Complete small-capacity steam power plant which uses only an injector for boiler feeding.

511. An Injector For Feeding Water To a Boiler (Figs. 443 and 444) has a thermal efficiency of about 99 per cent. That is, with the exception of about 1 per cent., all of the heat which is contained in the steam upon its admission to the injector is either expended in doing useful work, or is returned to the boiler as heat. From this it would appear to be almost impossible to find a more efficient device for feeding the boiler. This is true for those steam power plants such as a locomotive where a feed-water heater is not provided. But the efficiency of an injector as a pumping unit alone is only about 1 or 2 per cent. A stationary steam power plant usually has sufficient exhaust steam from the engine, the condenser pumps or other auxiliaries (Sec. 515) to heat the feed water, which steam if not used for this purpose would be wasted. Therefore, since an injector will not handle water at a temperature exceeding about 150° F., and since boiler feed water can be readily heated to about 210° F. with exhaust steam, a pump for boiler feeding is generally more economical than is an injector. Furthermore, under conditions of extreme variation in steam pressure, the operation of an injector is somewhat irregular and uncertain. However, due to simplicity, compactness, low first cost, and low maintenance cost, the injector is particularly applicable as a stand-by unit for boiler feeding. The principle of operation of an injector is explained below.

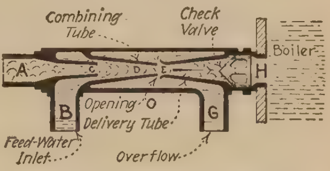


FIG. 444.—Sectional view of elementary injector illustrating the principle of operation.

EXPLANATION.—THE PRINCIPLE OF OPERATION OF ALL INJECTORS IS ESSENTIALLY AS FOLLOWS: In starting the injector, steam from the boiler is admitted to the injector at *A*, Fig. 444, and flows through nozzle *C*, tube *D*, the opening *O*, and out to the atmosphere through the overflow *G*. The friction of the steam, issuing at high velocity from *C*, draws the air from the feed-water inlet *B*, thus causing the water to rise therein until the steam issuing from *C* strikes the water. The steam, which is emerging from *C* at a high velocity condenses on meeting the water and imparts a considerable momentum to the water. The kinetic energy which is thus acquired by the mass of water is sufficient to carry it across the opening, *O*, to open the check valve, *H*, and to force it into the boiler against the boiler pressure. After the water starts to flow across the opening, *O*, the steam ceases to escape from *G*.

512. The Two Types Of Boiler-feed Pumps Which Are Most Frequently Used are: (1) *Piston pumps*, Fig. 446.

(2) *Centrifugal pumps* (Fig. 445). The principal of operation of each is described below. Piston pumps are generally either direct-acting or power driven. In a *direct-acting steam pump* (Fig. 446), the steam piston is directly connected to the water piston by the piston rod. The steam is usually admitted to the steam cylinder throughout the entire stroke. In a *power-driven piston pump* the water piston is actuated through a crank mechanism which is ordinarily driven by a steam cylinder, an electric motor, an internal-combustion engine, or from a line shaft. Centrifugal boiler-feed pumps (Fig. 445) are

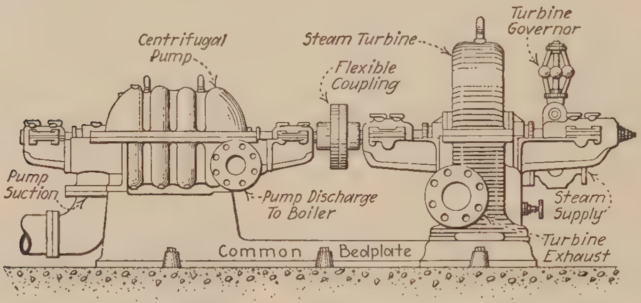


FIG. 445.—Centrifugal boiler-feed pump driven by a non-condensing steam turbine.

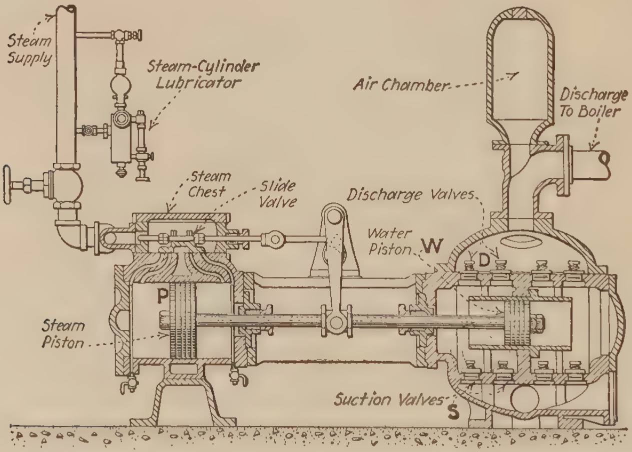


FIG. 446.—Section through a direct-acting duplex boiler-feed pump.

ordinarily driven by either an electric motor or by a steam turbine. The total capacity of the boiler-feed pump should be such that it will deliver about 50 gal. of water per hour for each rated boiler horsepower (Sec. 500).

Note.—The Tendency In Modern Practice In Boiler-feeding Is Toward The Use Of Centrifugal Pumps. However, one direct-acting steam pump is practically always provided for stand-by service. Centrifugal pumps have no suction or discharge valves to wear and no piston to keep packed. Consequently, the decrease in the efficiency of a centrifugal pump due to wear in service is practically zero. The direct-acting piston pump is, probably, more reliable for continuity of service than is a centrifugal pump, whereas the overall efficiency of the centrifugal pump is generally higher than is that of the steam pump.

Explanation.—The Direct-acting Piston Pump For Boiler Feeding (Fig. 446) is usually of the duplex type. That is two pumps, one of which is shown in Fig. 446, are mounted side by side and integral with each other. The steam valves of each are so actuated that when one of the pistons is in the stationary position at the end of its stroke, the other piston is moving. Thus, the discharge of water from a duplex pump is continuous. The operation of each unit of the pump is as follows: Steam is admitted throughout the entire stroke to first one side of the steam piston, *P*, and then the other. The steam is admitted to and exhausted from the cylinder by the operation of a D-slide valve in essentially the same manner as explained in Sec. 502 for the steam engine. The reciprocating motion thus imparted to the steam piston is transmitted to the water piston, *W* (Fig. 446). The suction valves, *S*, and discharge valves, *D*, are so operated by the water pressure, which is caused by the moving of the water piston, that the water which is drawn into the water cylinder through the suction valves, *S*, on one stroke is forced out through the discharge valves, *D*, on the next stroke.

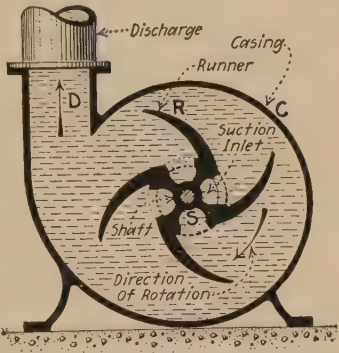


Fig. 447.—Illustrating the operating principle of the centrifugal pump.

Explanation.—The Operation Of A Centrifugal Pump may be understood by referring to Fig. 447. The water is admitted to the pump around the shaft through the suction inlet, *S*. It is discharged at *D*. The pump must first be "primed;" that is, the casing, *C*, must, in some way, be entirely filled with water. After the pump is primed, the runner, *R*, is rotated, say, by an electric motor or a steam turbine, at a high speed in the direction indicated by the arrow. The rotation of the runner causes the water which is within the casing to rotate. Due to the centrifugal force which is thus set up by the rotation of the water, a high pressure is created around the periphery of the casing. This water pressure causes the water in *D* to rise. As the water in *D* rises, the "suction" which is thus created within the casing causes more water to be drawn into the pump at *S*. Thus, the action is continuous in drawing water in at *S* and forcing it out through *D*.

513. The Function Of A Steam-power-plant Condenser (*C*, Fig. 423) is to condense the exhaust steam from a steam engine or a steam turbine and thereby increase the economy of the plant. By exhausting the air from a suitably designed vessel—condenser—which is connected to the exhaust of an engine or turbine, and then by entrapping the exhaust steam therein and cooling it, part of the steam will condense. If a vessel which contains only steam at atmospheric pressure and 212° F. is cooled to 60° F., the pressure within the vessel will be lowered from 14.7 to about 0.25 lb. per sq. in., abs. Although such a low pressure is seldom attained in practice, the use of a condenser usually lowers the back pressure on an engine or turbine from about 17 to 18 lb. per sq. in., abs., to somewhere around 0.5 to 2 lb. per sq. in., abs. Thus, by operating a steam engine or steam turbine condensing, less steam is required to develop a given amount of power than when operating non-condensing. The saving in steam with condensing operation over that of non-condensing operation is ordinarily from about 20 to 30 per cent. With condensing operation maximum economy in overall cost of operation is provided when the condenser vacuum gage reading (the pressure in the condenser) is about as follows: (1) *For reciprocating steam engines,* 26.5 *in. of mercury.* (2) *For steam turbines about* 28.5 *in. of mercury.* Steam-power-plant condensers are described briefly in the following sections.

Note.—The Theoretical Money Saving Due To The Installation Of Condensers May Not Always Be Realized, particularly in small plants and for small prime movers. This is because of the initial and maintenance expense of the condenser and of the auxiliaries which are necessary for its operation. Under certain conditions the expense of condenser operation may be greater than the saving effected by the condenser. Condensers are seldom economically justified in plants of capacities less than, say, 400 hp.

514. The Two Principal Types Of Condensers are: (1) *The surface condenser*, Fig. 448, wherein the exhaust steam and the cooling water are separated by the walls of metal tubes. (2) *The jet condenser*, Fig. 449, wherein the exhaust steam and the cooling water are mixed together. Jet condensers may be classified according to the method of removing water and air from the condenser, as: (*a*) *Low-level jet condenser*, Fig. 449 wherein the condensed steam, the cooling water, and the air are removed by pumps. (*b*) *Siphon jet condenser*, sometimes called a *barometric condenser* (Fig 297), wherein the condensed steam, the cooling water, and sometimes the air, are removed by a barometric column. (*c*) *Ejector jet condenser* wherein the condensed steam, the cooling water, and the air are removed by the ejector effect of the cooling water. The operation of a typical surface condenser and of a low-level jet condenser is explained below. Condensers of each of these types have applications for which they are best fitted. Where the cooling water is "bad" and hence cannot be permitted to mix with the boiler-feed water the use of a surface condenser is usually imperative. Where cooling water is scarce or expensive, the same water may be used over and over again by cooling it in a *cooling tower* (Fig. 290) or in a cooling pond (Figs. 289 and 291).

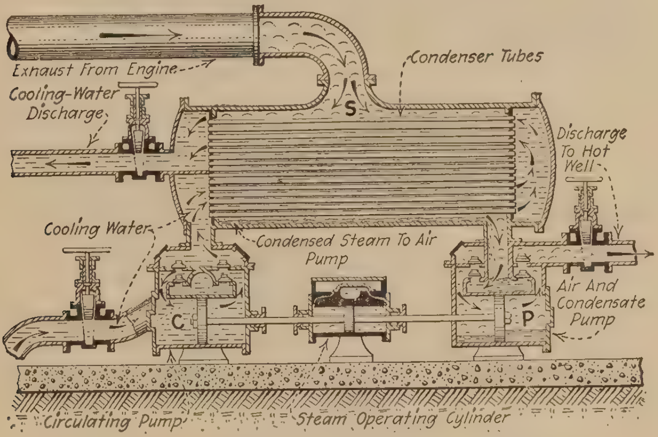


Fig. 448.—Illustrating the operation of a surface condenser.

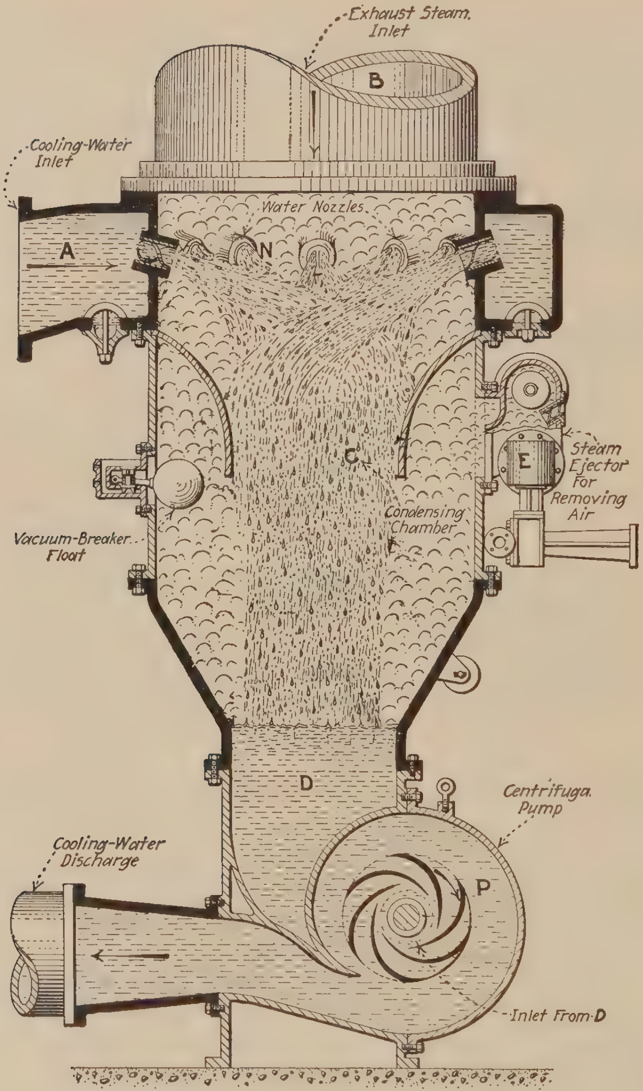


Fig. 449.—An Elliot-Erhart low-level jet condenser.

Explanation.—The Operation Of A Surface Condenser is as follows: The cooling water is pumped through the condenser tubes (Fig. 448) by the circulating pump, *C*. The exhaust steam from the engine or turbine enters the condenser at *S*, and comes in contact with the metal tubes which contain the cooling water. Since the temperature of the exhaust steam is higher than that of the cooling water, heat flows from the steam through the metal walls of the tubes and into the water. The heat which is thus given up by the steam causes it to condense to water, which falls to the bottom of the condenser. The heat which is absorbed from the steam by the water is carried out of the condenser by the cooling water. The condensed steam, together with any air which may enter the condenser with the steam, is removed by the pump *P*.

Explanation.—The Operation Of A Low-level Jet Condenser (Fig. 449) is as follows: The cooling water enters the condenser at *A* and is broken up into a fine spray by the nozzles, *N*. The exhaust steam from the engine or turbine enters the condenser at, *B*, mixes with the cooling water spray and is condensed in the condensing chamber, *C*. The mixture of condensed steam and cooling water falls by gravity to the bottom, *D*, of the condenser from which it is removed by the centrifugal pump, *P*. In the particular condenser shown in Fig. 449, air is removed from the condenser by a *steam-ejector*, *E*.

515. For Successful Operation Of Condensers, Pumps Must Ordinarily Be Used (Fig. 423) to circulate the cooling water, to remove the condensed steam—condensate—from the condenser, and to remove the air which is entrained with the exhaust steam and which leaks in at the fittings. The pumps which are used in conjunction with condensers are: (1) *Circulating pumps*, *C*, Fig. 448, and *P*, Fig. 449, to supply the cooling water, or in the case of low-level jet condensers to remove the mixture of cooling water and condensate. (2) *Wet-vacuum pumps*, *P*, Fig. 448, for removing both the condensate and air from a surface condenser. (3) *Dry-vacuum pumps*, *E*, (Fig. 449) for removing only the air from a surface or jet condenser. (4) *Condensate pumps* for removing only the condensate from surface condensers. Piston pumps (Sec. 512) and centrifugal pumps are used as circulating pumps, wet-vacuum pumps, and condensate pumps. Dry-vacuum pumps are usually of the piston type, steam-oreject type, or hurling-water type. The trend of recent large capacity installations seems to be toward the use of electric-motor or steam-turbine driven centrifugal pumps for circulating and condensate pumps, with a steam-ejector or hurling-water dry-vacuum pump. The power which is required to operate the condenser pumps varies from 1 to 6 per cent. of that of the main prime mover, depending upon the type of apparatus and local conditions.

516. The Three Main Reasons Why The Boiler Feed Water Should Be Heated Before It Is Admitted To The Boiler are: (1) *The introduction of cold water—at a temperature of* 60 *or* 70° *F.—into the boiler is likely to strain the hot plates and the riveted joints*, thus causing the boiler to leak. (2) *By heating the water before it enters the boiler a large quantity of scale-forming impurities may be precipitated* outside of the boiler and are thus prevented from entering the boiler. (3) *A considerable quantity of heat may be returned to the boiler which would otherwise be lost in the exhaust steam or boiler chimney gases*, thereby effecting a material decrease in the quantity of fuel necessary (Sec. 484). Apparatus of various types for heating boiler feed water are described in the sections immediately following.

517. The Two Principal Sources Of Heat For Preheating The Boiler Feed Water are: (1) *Exhaust steam*, Sec. 518. (2) *Flue gases*. A device (*H*, Fig. 423) in which the feed water is preheated by exhaust steam is called a *feed-water heater* (Sec. 518). A device in which the feed water is heated by the flue gases is called a *fuel economizer* (Sec. 521). Live steam is sometimes used to heat the feed water. However, this method is comparatively uneconomical and is only used in special cases.

518. The Heat Which Is Utilized In Heating The Feed Water By An Exhaust-steam Feed-water Heater is, principally, the latent heat of vaporization (Sec. 364) of the exhaust steam. That is, when the exhaust steam is condensed in the feed-water heater (Figs. 450 and 451) the latent heat of vaporization of the exhaust steam—about 970 B.t.u. per lb. of steam condensed—is given up to the feed water. The maximum temperature to which the feed water is ordinarily heated in a feed-water heater is about 210° F. Therefore, if the feed water is supplied to the heater at, say, 50° F. and is heated by it to 210°F., each pound of feed water absorbs: $(210 - 50) = 160$ *B.t.u.* in passing through the heater. Consequently: $(970 \div 160) =$ *approximately* 6 *lb.* of feed water will have its temperature raised from 50° F. to 210° F. by each pound of exhaust steam which is condensed. The weight of exhaust steam required to heat the feed water is only from about 9 to 14 per cent. of the steam generated by the boiler. For non-condensing prime movers part of the exhaust steam from the engine or turbine and the boiler-feed pump may be used for feed-water heating. If the prime mover is operated condensing, the exhaust steam for feed-water heating is usually supplied by steam-driven auxiliaries such as the boiler-feed pumps (Sec. 512) and the condenser pumps (Sec. 515).

519. The Two Principal Classifications Of Feed-water Heaters are: (1) *Open heaters*, Fig. 450, wherein the exhaust steam mixes with the cold feed water. (2) *Closed heaters*, wherein the exhaust steam and the cold feed water are separated by the walls of metal tubes. The operation of a heater of each type is briefly explained below. Open feed-water heaters should be used when possible because they are more efficient, better water purifiers, and are more easily cleaned than are closed heaters. However, a closed heater must be used under the following conditions: (1) *When the steam pressure within the heater is much above or below atmospheric.*

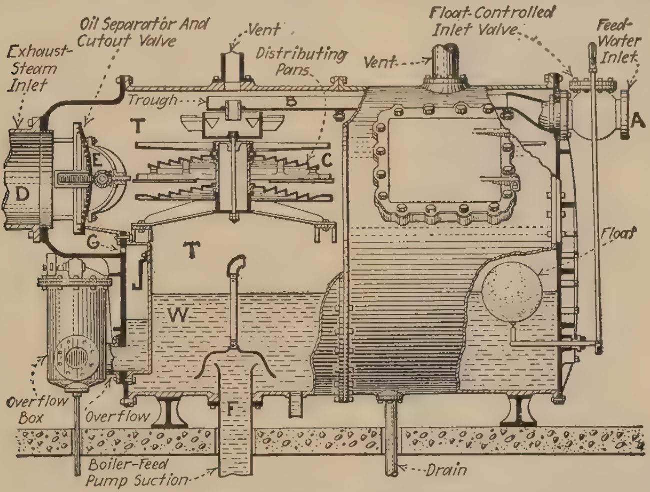


FIG. 450.—Partial sectional view of an open feed-water heater of the horizontal type. (Elliot Co., Pittsburgh, Pa.)

(2) *When the feed-water heater is connected between the boiler-feed pump and the boiler.*

EXPLANATION.—THE OPERATION OF THE ELLIOTT OPEN FEED-WATER HEATER (Fig. 450) is essentially as follows: The feed water enters the heater at *A*, and flows down the trough, *B*, to the distributing pans, *C*, where it spills over and is broken up into small drops as it falls to the bottom of the heater. The exhaust steam enters the heater at *D*, and passes through the oil separator, *E*, and enters the tank, *T*. When the exhaust steam mixes with the falling water, the steam is condensed. In the condensing, the latent heat of vaporization of the steam is given up to the water. Thus the water, *W*, which collects in the bottom of the tank, may be heated to about 210° F. The boiler-feed pump removes the heated water at *F* and discharges it into the boiler. The entrained water and oil which is separated from the exhaust steam at *E* is piped to the overflow box at *G*.

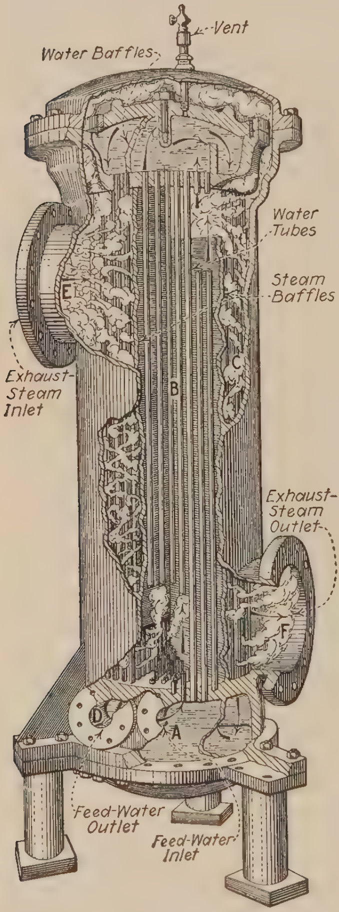


FIG. 451—A Blake & Knowles vertical closed feed-water heater. The steam rises in the compartment *B*, but to insure clarity, it is not shown in this illustration.

EXPLANATION.—THE OPERATION OF THE BLAKE & KNOWLES CLOSED FEED-WATER HEATER (Fig. 451) is as follows: The feed water which enters the heater at *A* flows upward through one nest of tubes, *B*, and downward through another nest of tubes, *C*. Six such nests of tubes are provided which are so baffled that the water passes through each nest in turn, thus traversing the length of the heater six times before it leaves the heater at *D*. The exhaust steam enters the heater at *E* and leaves it at *F*. The space between the water tubes is so baffled that the steam traverses the length of the heater three times. When the exhaust steam comes in contact with cold water-filled tubes, the steam condenses and gives up its latent heat of vaporization. The heat thus given flows through the walls of the water tubes and heats the water.

520. The Saving In Fuel Which Is Effected By A Feed-water Heater may be computed by the following formula:

$$X = \frac{(T_2 - T_1)}{\mathbf{H} - (T_1 - 32)} \qquad \text{(decimal)} \tag{345}$$

Wherein: X = the proportion of fuel which is saved by using a feed-water heater, expressed as a decimal. T_2 = the temperature of the feed water, in degrees Fahrenheit, leaving the feed-water heater. T_1 = the temperature of the feed water, in degrees Fahrenheit, entering the heater. **H** = the total heat above 32° F. in the steam, in British thermal units per pound, which is generated in the boiler; this value may be taken from a steam table. The saving in fuel as obtained by the above formula is, for an exhaust-steam feed-water heater, practically all a net gain. A feed-water heater will prove economical in all steam power plants (except, possible, where fuel is extremely cheap) and will much more than justify its cost.

EXAMPLE.—The temperature of the feed water which is being supplied to a boiler is 60° F. The boiler generates dry saturated steam at a pressure of 150 lb. per sq. in. gage. What will be the saving in fuel if a feed-water heater is installed which heats the feed water to a temperature of 210° F.? SOLUTION.—From the steam table (Table 394), *the total heat of* 1 *lb. of dry saturated steam at a pressure of* 150 *lb. per sq. in. gage* = 1,195 B.t.u. By For. (345) *the saving*, $X = (T_1 - T_2)/[\mathbf{H} - (T_1 - 32)] = (210 - 60) \div [1{,}195 - (60 - 32)] = 150 \div 1{,}167 = 0.128$ or 12.8 *per cent.*

521. A Fuel Economizer (Fig. 452) consists of a number of vertical tubes which connect to a header. The fuel economizer is interposed in the path of the flue gases between the last pass of the boiler and the chimney. The feed water enters the economizer tubes at *A* (Fig. 452) and leaves them at *B*. When the products of combustion—the flue gases—leave the boiler they are ordinarily at a temperature of from 450° to 700° F. By passing the flue gases over the tubes of an economizer, their temperature may be reduced to a value say, between 225° and 400° F. This reduction in temperature is caused by a portion of the heat in the flue gases being transferred to the feed water in the economizer. The average temperature of the feed water upon ecentran to the economizer varies, in different installations, from about 60° to 200° F., the average being about 140° F.; that at the exit varies from about 200 to 325° F., the average being about 260° F. Thus, it is evident that the use of a fuel economizer results in the saving of a portion of the heat which is ordinarily lost in the flue gases (Sec. 484). Fuel economizers are sometimes connected in series with exhaust-steam feed-water heaters. Then the feed water is first heated in the feed-water heater, after which, it is passed through the economizer wherein its temperature is still further increased. In other cases the feed-water is pumped directly from the hot-well, or other source of supply, directly to the economizer.

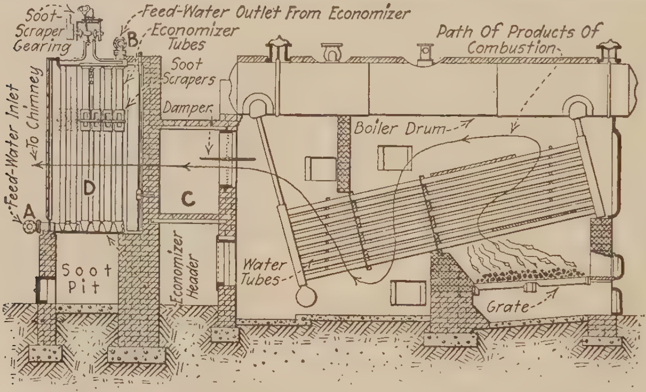


Fig. 452.—Typical installation of a fuel economizer. The gases travel horizontally away from the reader in *C* and return toward the reader through the economizer at *D* and thence to the chimney.

Note.—The Theoretical Money Saving Due To Economizer Installation May Not Always Be Realized, particularly in small plants, because of the initial and maintenance expense of the economizer and because its installation reduces the chimney gas temperature and thereby tends to interfere with the production of draft (Sec. 256). In fact, economizers seldom are economical in plants of capacities of less than, say, 500 hp.

522. The Theoretical Saving In Fuel Which Is Obtained By Using A Fuel Economizer may be computed by For. (345), Sec. 520, by substituting for T_1 and T_2, respectively, the temperatures in degrees Fahrenheit of the feed water as it enters and as it leaves the economizer. However, the actual saving which is effected by the economizer will be less than the value so obtained because of the power which is required to drive the economizer soot-scrapers and because of the extra power which will be required to force the gaseous products of combustion through the economizer. On account of the additional restriction which is offered by an economizer to the passage of the flue gases, the use of an economizer practically always requires that the draft pressure be maintained by artificial means (Sec. 524). Thus, with a natural-draft furnace, the installation of a fuel economizer may result in such poor combustion that the overall economy of the plant will actually be decreased. In large installations of, say about 500 hp. and above, where the load is such as to require operation of the boilers considerably above their rated capacity, an economizer may effect a fuel saving of from 5 to 20 per cent.

523. A Superheater (*S*, Fig. 427 and Fig. 335) is a device consisting of some sort of piping arrangement, which is exposed to hot furnace gases, through which the steam passes after it leaves the boiler drum. The superheater may be located in the boiler furnace or in a separate superheater furnace. In either case the steam is superheated (Sec. 356) as it passes through the superheater. The total temperature of the superheated steam in American practice does not ordinarily exceed 500 or 600° F. The use of superheated steam generally increases the economy of the plant, particularly medium and large-capacity plants. The principal reasons for this are that with superheated steam: (1) *The water rate* (Sec. 507) *of the prime mover is reduced.* (2) *There is less heat loss both in the piping and within the prime mover.*

Note.—The Water Rate Of A Steam Prime Mover Is Decreased By Superheating The Steam, but the decrease is not, ordinarily, so great for a steam turbine as it is for a steam engine. The decrease in the water rate is, for a steam engine about 1 per cent. for every 6° F. of superheat, and for a steam turbine about 1 per cent. for every 10° F. of superheat. But, since the water rate is not necessarily indicative of the overall economy (Sec. 526) of the plant, the actual monetary saving which is effected by using superheated steam must be determined for every installation. The actual saving depends upon so many variable factors that no general rule covering it can be given. However, in general, the use of superheated steam will, for large installations, result in a considerable saving as compared to the use of saturated steam. Superheating saves fuel by minimizing the condensation of the steam in the piping and the heat engines. Condensed steam represents, in general, a non-recoverable heat loss and furthermore it causes friction losses in the piping and heat engines.

524. Artificial Draft Apparatus is any apparatus for increasing the amount of air for combustion which flows through the furnace above that which is produced by the chimney. If chimneys were all built sufficiently large and high, artificial draft would never be needed. However, the building of sufficiently-large chimneys would frequently entail a prohibitive initial cost. Consequently, some sort of artificial draft apparatus (Sec. 525) will probably prove economical under the following conditions: (1) *When the temperature of the chimney gases is low, as when an economizer is used.* (2) *When the boilers are to be worked greatly in excess of their normal rating.* (3) *When fuels which require intense draft pressure are used.* (4) *When certain kinds of stokers, such as the underfeed, are used.* (5) *Where balanced draft* (Sec. 525) *is desired.* Practically all artificial draft is used in conjunction with the natural draft provided by the chimney.

525. The Apparatus Used In The Production Of Artificial Draft is, usually, either: (1) *A steam jet,* Figs. 453 and 454, wherein the draft pressure is produced by a jet of live steam issuing from an orifice.

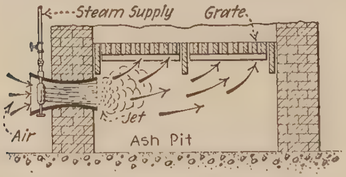


Fig. 453.—Steam-jet forced draft.

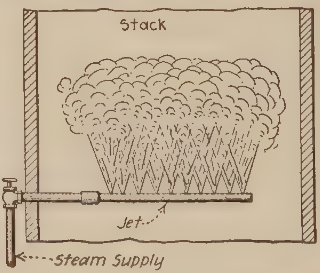


Fig. 454.—Steam-jet induced draft.

(2) *A fan or blower.* The fan or blower is usually driven by an electric motor or a steam turbine. When artificial draft is produced by a fan or blower it is called *mechanical draft.* There are three kinds of artificial draft: (1) *Forced draft,* Figs. 453 and 455, wherein the ash pit is made tight, and the apparatus—blower or steam jet—supplies air to it at

a pressure above atmospheric. (2) *Induced draft* (Figs. 454 and 456) wherein the apparatus draws the furnace gases from the furnace outlet and forces them up the chimney. Thus, with induced draft the pressure within the furnace is ordinarily below atmospheric. (3) *Balanced draft*, which is a combination of forced and induced draft, which is ordinarily so arranged that the pressure within the furnace is automatically maintained at practically atmospheric or just a little below atmospheric.

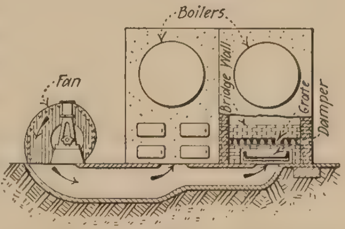


FIG. 455.—Mechanical forced draft.

NOTE.—THE ADVANTAGES AND DISADVANTAGES OF THE THREE KINDS OF ARTIFICIAL DRAFT which are mentioned above may be briefly stated as follows: (1) *With forced draft*, the pressure within the furnace tends to prevent the leakage (Sec. 493) of cold air inward through the setting. However, this pressure within the furnace may force some of the furnace gases out through the fire doors or other openings and thus contaminate the air of the boiler room with the pungent furnace gases. (2) *With induced draft*, any tendency for the leakage of air into the furnace through cracks in the setting is augmented, because the pressure within the furnace is less than that of the air on the outside. But this reduced pressure within the furnace tends to prevent the furnace gases from escaping into the boiler room. (3) *With balanced draft*, there is neither a tendency for the air to leak through the boiler setting nor for the furnace gases to escape into the boiler room. The fire is not affected by opening the furnace doors for adding coal or fixing the fire. Very finely-divided fuel can be burned. High rates of combustion can be realized without any appreciable detriment to the economy. Balanced draft, however, ordinarily requires a duplicate set of steam jets, blowers, or fans.

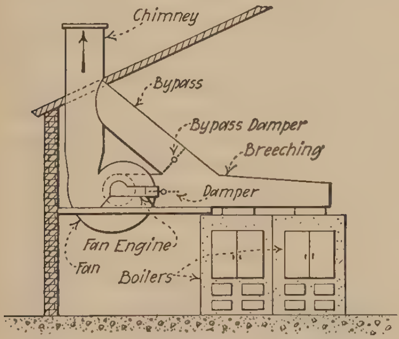


FIG. 456.—Mechanical induced draft.

526. There Are Several Methods Of Expressing The Overall Efficiency Of An Entire Steam Power Plant, among which are: (1) *The number of pounds of fuel required per unit of energy* *output.* This method of expressing the efficiency is, unless the heat content of the fuel is known, rather indefinite. (2) *The quantity of heat energy, in British thermal units, (in the fuel) which is required to produce one unit of energy output.* (3) *The percentage ratio of the energy output to the heat input in the fuel.* In each of the above methods of expressing the efficiency, the energy output may be measured in kilowatt-hours at the generator terminals, or in horsepower-hours measured either at the shaft of the prime mover (Sec. 507), or within the engine cylinder (Sec. 504). Whatever method is used, there should always be included a statement as to where the energy output was measured. The method of computing each of the above efficiencies is explained in the following notes. The overall efficiency may be useful for comparing the operation of two or more power plants, or for comparing the operation of one power plant during different periods, such as the performance of different shifts. However, if the thermal efficiency of a plant is, say 10 per cent. the question immediately arises as to what happened to the other 90 per cent. of the heat. The destination of the other 90 per cent. may be determined by making a complete test of the plant, and then tabulating the results of the test into a "heat balance" (Sec. 527).

NOTE.—TO DETERMINE THE OVERALL EFFICIENCY OF A STEAM POWER PLANT IN TERMS OF THE NUMBER OF POUNDS OF FUEL REQUIRED PER UNIT OF ENERGY OUTPUT, it is necessary to weigh the fuel which is consumed during a given period and to measure the energy output for the same period. Then, the overall efficiency of the plant during that period may be computed by the following formula:

$$W = \frac{W_T}{e} \qquad \text{(pounds per energy unit)} \tag{346}$$

Wherein: W_T = the total weight, in pounds, of the fuel consumed during the given period. e = the total energy output, in kilowatt-hours or in horsepower-hours, during the given period. Then W = the number of pounds of fuel consumed per kilowatt-hour, per brake horsepower-hour or per indicated horsepower-hour, as e is expressed in kilowatt-hours, brake horsepower-hours, or indicated horsepower-hours.

NOTE.—THE OVERALL EFFICIENCY OF A STEAM POWER PLANT, EXPRESSED IN TERMS OF THE NUMBER OF BRITISH THERMAL UNITS SUPPLIED AS FUEL PER UNIT OF ENERGY OUTPUT, may be determined by the following formula:

$$Q = H \times W \qquad \text{(B.t.u. per energy unit)} \tag{347}$$

Wherein: W = the number of pounds of fuel consumed per unit of energy output as determined by For. (346). H = heating value, in British thermal units per pound, of the fuel (Sec. 452). Then Q = the heat, in British thermal units which must be supplied as fuel to produce one unit of energy output in which e of For. (346) was expressed. Thus, Q may be expressed as the number of British thermal units per kilowatt-hour or per horsepower-hour measured either at the prime mover shaft (per brake horsepower-hour) or in the engine cylinder (per indicated horsepower-hour).

NOTE.—THE OVERALL THERMAL EFFICIENCY, which is the ratio of the heat equivalent of the mechanical or electrical energy output to the heat input as fuel, may be computed as follows:

If the energy output is measured in kilowatt-hours at the generator terminals, use the following formula:

$$E_G = \frac{3{,}413}{Q_G} \quad \text{(decimal)} \tag{348}$$

Wherein: E_G = the overall engine and generator efficiency referred to the kilowatts developed by the generator, expressed decimally. Q_G = the heat in British thermal units in the fuel required to produce 1 kw.-hr. at the generator terminals as determined by For. (347).

If the energy output is measured in horsepower-hours within the engine cylinder, use the following formula:

$$E_T = \frac{2{,}545}{Q_T} \quad \text{(decimal)} \tag{349}$$

Wherein: E_T = the actual thermal efficiency, expressed decimally, referred to the indicated horsepower (the energy output is measured within the engine cylinder). Q_T = the heat in British thermal units per indicated horsepower-hour as determined by For. (347).

If the energy output is measured in horsepower-hours at the prime mover shaft, use the following formula:

$$E_E = \frac{2{,}545}{Q_E} \quad \text{(decimal)} \tag{350}$$

Wherein: E_E = the overall engine efficiency, expressed decimally, referred to the brake horsepower (energy output measured at prime mover shaft). Q_E = the heat, in British thermal units per brake horsepower-hour, as determined by For. (347).

EXAMPLE.—In a test of a steam power plant for a given period of time the total energy developed was 9,000 kw.-hr. During the same period 27,600 lb. of coal was fired. The heating value of the coal as fired was 12,800 B.t.u. per lb. How many pounds of coal and what quantity of heat were consumed per kilowatt-hour? What was the overall engine and generator efficiency referred to the generator output? SOLUTION.—By For. (346), *the coal consumption*, $W = W_T/e = 27{,}600 \div 9{,}000 =$ *3.06 lb. per kw.-hr.* By For. (347), *the heat supplied in the fuel*, $Q_G = H \times W = 3.06 \times 12{,}800 = 39{,}168$ *B.t.u. per kw.-hr.* By For. (348), *the* *overall engine and generator efficiency referred to the kilowatt output of the generator,* $E_G = 3{,}413/Q_G = 3{,}413 \div 39{,}168 = 0.087{,}1$ or 8.71 *per cent.*

527. The "Heat Balance" Of An Entire Steam Power Plant consists of a quantitative tabulation of values obtained by test and calculation of the distribution or destination of the heat which is contained in the fuel as fired. Table 528 shows an example of a heat balance of a steam power plant which is tabulated in accordance with the "A. S. M. E. Test Code, 1915." It is called a "balance" because in it the sum of all of the British thermal units consummed—usefully or wastefully—must equal the British thermal units supplied; that is, these amounts must balance. The various destinations of the heat which was contained in the 1 lb. of coal of Table 528 is shown graphically in Fig. 457. A pictorial representation of a heat balance of a simple stationary plant is shown in Fig. 458, and that for a locomotive engine is shown in Fig. 459; see also the frontispiece. By making a complete test of a steam power plant, and then by arranging the data obtained therefrom into a "heat-balance" (Table 528), information is available whereby the operator may be guided in improving the overall economy of the plant by decreasing certain of the heat losses.

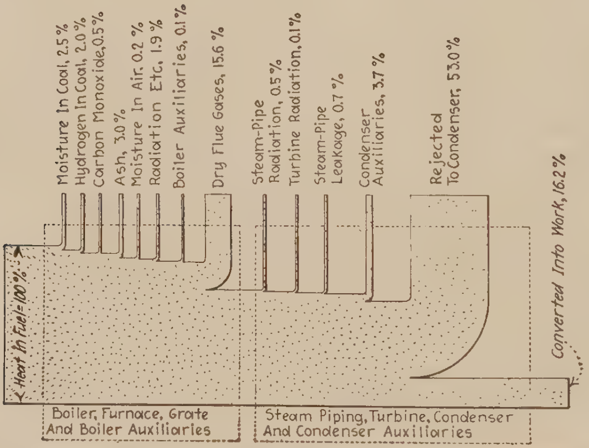


FIG. 457.—Graphical representation of the steam-power-plant heat balance which is tabulated in Table 528.

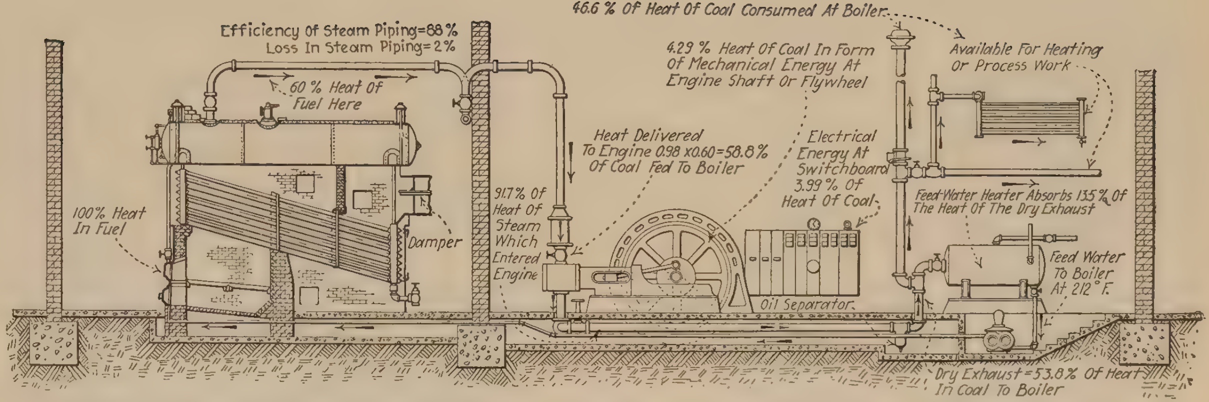

Efficiency Of Steam Piping=88 %
Loss In Steam Piping=2 %
60 % Heat Of Fuel Here
100% Heat In Fuel
Damper
46.6 % Of Heat Of Coal Consumed At Boiler
4.29 % Heat Of Coal In Form Of Mechanical Energy At Engine Shaft Or Flywheel
Available For Heating Or Process Work
Heat Delivered To Engine 0.98 x0.60=58.8 % Of Coal Fed To Boiler
91.7 % Of Heat Of Steam Which Entered Engine
Electrical Energy At Switchboard 3.99 % Of Heat Of Coal
Feed-Water Heater Absorbs 13.5 % Of The Heat Of The Dry Exhaust
Feed Water To Boiler At 212° F.
Oil Separator
Dry Exhaust=53.8 % Of Heat In Coal To Boiler

FIG. 458.—Showing where the heat content of the fuel goes in a simple non-condensing stationary steam power plant. (*From Engineering Bulletin No. 2, United States Fuel Administration*). The efficiency of boiler and furnace depending upon refinement of equipment and operation, may range between 35 per cent and 84 per cent.

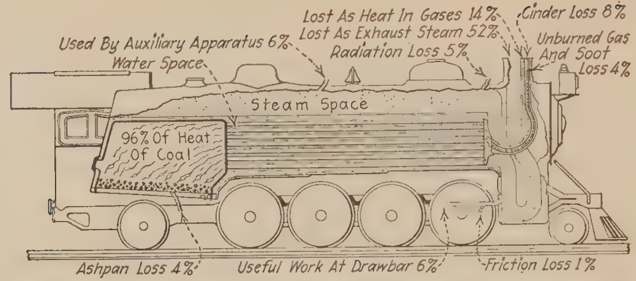

Lost As Heat In Gases 14%
Cinder Loss 8%
Used By Auxiliary Apparatus 6%
Lost As Exhaust Steam 52%
Unburned Gas And Soot Loss 4%
Radiation Loss 5%
Water Space
Steam Space
96% Of Heat Of Coal
Ashpan Loss 4%
Useful Work At Drawbar 6%
Friction Loss 1%

Fig. 459.—Illustrating the destination of the heat content of the fuel which is fired in a steam locomotive.

528. Table Showing An Example Of A Heat Balance Of A Steam Power Plant.—(In accordance with "A. S. M. E. Power Plant Test Code, 1915.") See Div. 14 for explanation of various items under "Boiler Losses."

Items	B.t.u. Per Lb. Coal As Fired	Per Cent.
1. Heat Units In Coal	13,500	100.0
2. Boiler Losses		
(a) Loss due to evaporation of moisture in coal	338	2.5
(b) Loss due to heat carried away by steam formed by the burning of hydrogen	270	2.0
(c) Loss due to heat carried away in the dry flue gases	2,106	15.6
(d) Loss due to carbon monoxide	67	0.5
(e) Loss due to combustible in ash and refuse	405	3.0
(f) Loss due to heating moisture in air	27	0.2
(g) Loss due to unconsumed hydrogen and hydrocarbons, to radiation, and unaccounted for	257	1.9
(h) Heat supplied steam-driven appliances for operating boilers less that recovered by heating feed water	13	0.1
(i) Total Boiler Losses	3,483	25.8
3. Engine Consumption		
(a) Radiation from steam pipe	67	0.5
(b) Radiation from engine or turbine	13	0.1
(c) Heat rejected to condenser	7,155	53.0
(d) Heat withdrawn from engine receivers or turbine stages for other use than heating feed water	0	0.0
(e) Heat lost by leakage of steam piping	95	0.7
(f) Heat converted into work	2,187	16.2
4. Heat In Steam Supplied For Purposes Foreign to engine or turbine	500	3.7
Totals (same as Item 1)	13,500	100.0

QUESTIONS ON DIVISION 15

1. What is the function of a *steam power plant?* Explain briefly how this function is performed.

2. Name the essential parts of a steam power plant.

3. Describe fully the function of: (*a*) The boiler furnace. (*b*) The combustion chamber. (*c*) The boiler. (*d*) The steam piping. (*e*) The prime mover.

4. Name the principal types of *boiler furnaces.*

5. How may *boilers* be classified? What is a *fire-tube boiler?* A *water-tube boiler?*

6. Name three principal types of fire-tube boilers.

7. What is an *externally-fired boiler?* An *internally-fired boiler?*

8. Name the general applications for which boilers of the different types are particularly well adapted.

9. How is the efficiency of a boiler and furnace determined?

10. Explain what is meant by a *boiler horsepower.* How are boilers rated by the manufacturers?

11. What two kinds of prime movers are generally used in a steam power plant?

12. Describe with sketch the operation of a simple D-slide-valve steam engine.

13. Draw a typical *indicator diagram* and indicate thereon the location of: (*a*) The point of cut-off. (*b*) The point of release. (*c*) The admission line. (*d*) The expansion line. (*e*) The exhaust line. (*f*) The compression line. (*g*) The atmospheric line.

14. How can the power which is developed in the engine cylinder be determined?

15. What is meant by *indicated horsepower?*

16. What are the principal applications of *steam turbines?*

17. Name the two principal types of steam turbines.

18. Explain briefly how the heat energy in the steam is converted into mechanical work by an *impulse turbine.* By a *reaction turbine.*

19. Give the formula for computing the thermal brake efficiency of a steam prime mover.

20. How are steam prime movers rated?

21. Define *water rate.* When is the water rate of a prime mover indicative of its efficiency?

22. Name the principal *auxiliaries* which are frequently used in steam power plants. In general, what is the purpose of the auxiliaries?

23. What are the two principal types of boiler-feeding apparatus?

24. Explain the operation of a simple *injector.* What are some of the advantages and disadvantages of an injector for boiler-feeding?

25. What two types of *pumps* are generally used for boiler-feeding? Explain the operation of each.

26. Why is a *centrifugal pump* preferable to a *piston pump* for boiler-feeding?

27. What is the function of a *condenser?* Explain how it performs this function. What is the percentage of saving in steam which a condenser may be expected to provide?

28. Name the two principal types of condensers. Explain briefly how each operates.

29. Describe briefly the operation of each of the principal types of jet condensers.

30. For what purposes are pumps used in conjunction with the operation of condensers? What types of pumps are generally used for these purposes?

31. State three reasons why the boiler feed water should be heated before it is admitted to the boiler.

32. What are the two principal sources of heat which are utilized in preheating the boiler feed water?

33. Explain how 1 lb. of exhaust steam at atmospheric pressure will raise the temperature of about 6 lb. of feed water from about 50° F. to 210° F.

34. What are the two principal types of *feed-water heaters?* Explain briefly the operation of a feed-water heater of each type. Which type is preferable? Under what conditions must a closed heater be used?

35. Show how to compute the saving in fuel which may be effected by a feed-water heater.

36. What is a *fuel economizer?* Explain its operation.

37. Explain why the actual saving which is effected by a fuel economizer is less than the theoretical saving.

38. Under what conditions may the installation of a fuel economizer actually decrease the economy? Under what conditions may it increase the economy?

39. What is a *superheater?* Where may a superheater be located?

40. Give the principal reasons why the use of a superheater increases the economy of the plant.

41. What is *artificial draft?*

42. Under what conditions may artificial draft prove economical?

43. What are the two different kinds of apparatus which are used to produce artificial draft? Explain, the meaning of the following terms: (*a*) *Forced draft.* (*b*) *Induced draft.* (*c*) *Balanced draft.*

44. State the advantages and disadvantages of forced draft, induced draft, and balanced draft.

45. Give three methods of expressing the *overall efficiency* of an entire steam power plant. In what manner may the overall efficiency of a plant be useful?

46. Explain how each of the three methods (Question 45) of expressing the overall efficiency may be determined.

47. What is a *heat balance?*

48. How may the heat balance be used in increasing the overall efficiency of a power plant?

PROBLEMS ON DIVISION 15

1. If a boiler absorbs 8,000 B.t.u. for each pound of fuel fired, what is the boiler and furnace efficiency if a calorimeter test of the coal as fired shows that the heating value is 11,450 B.t.u. per lb.?

2. During a 10-hr. test of a steam power plant 5,350 lb. of coal was consumed, which had a heating value of 13,300 B.t.u. per lb. During the same period 55,120 lb. of dry saturated steam at a pressure of 150 lb. per sq. in., gage, was formed. The temperature of the boiler feed water was 210° F. What was the boiler, grate, and furnace efficiency?

3. During the test of Prob. 2, the double-acting simple Corliss engine was running at a speed of 200 r.p.m. The average mean effective pressure for the head-end and crank-end of the cylinder was 59.0 lb. per sq. in. The diameter of the piston was 16 in. the length of stroke was 22 in. The diameter of the piston rod was 2 in. What was the average indicated horsepower which was developed during the test?

4. Due to leakage, condensation, and steam consumption of the auxiliaries, the engine of Prob. 3 consumed only 94 per cent. of the steam which was generated by the boiler in Prob. 2. If the steam at the engine throttle was dry saturated at a pressure of 145 lb. per sq. in. gage, and the temperature of the exhaust was 220° F., what was the thermal brake efficiency if 90 per cent. of the power developed within the engine cylinder is delivered at the shaft?

5. What was the water rate per indicated horsepower-hour of the engine in Prob. 3?

6. The feed water for the power plant of Prob. 2, which was at a temperature of 70° F., was heated in an open feed-water heated to 210° F. by exhaust steam from the main engine. What saving in fuel was effected by thus heating the feed water?

7. What was the overall efficiency of the power plant of Prob. 2 and 3 referred to the indicated horsepower expressed in pounds of coal per indicated horsepower-hour, and in British thermal units per indicated horsepower-hour? What is the actual thermal efficiency?

8. If the scale of the spring which was used in taking the indicator diagram of Fig. 437 had been 50, what would have been the value of the mean effective pressure?

DIVISION 16

INTERNAL-COMBUSTION-ENGINE POWER PLANTS

529. In The Internal-combustion-engine Power Plant the fuel is burned within the engine cylinder. A part of the heat which is thus liberated within the engine cylinder is utilized in doing work on the piston. The products of combustion (Sec. 463) are the working medium. In the steam-engine power plant, the fuel is burned in a furnace. A part of the heat which is liberated by the combustion of the fuel in the boiler furnace is utilized in evaporating water to steam. The steam, which is the working medium, is then piped to the engine, whereupon a part of the heat energy in the steam is utilized in doing useful work. The use of an internal-combustion-engine power plant eliminates the radiation and steam-leakage losses from the boiler and piping of a steam power plant. Consequently, the thought arises that the internal-combustion-engine plant should, theoretically, be the more efficient of the two. This is true, although as explained in Sec. 550, the higher theoretical efficiency of the internal-combustion-engine plant is not wholly due to the reason stated above.

NOTE.—THE SUBJECT OF INTERNAL-COMBUSTION-ENGINE POWER PLANTS IN THE FOLLOWING ORDER IS TREATED IN THIS DIVISION: (1) *Fuels used.* (2) *Methods of mixing fuel with the air for combustion.* (3) *Methods of ignition.* (4) *Methods of governing.* (5) *Explanation of the operation of a two-stroke and a four-stroke cycle engine.* (6) *Classification of internal combustion engines according to compression pressure.* (7) *Description of various types of engines.* (8) *Testing and efficiencies.* (9) *Costs and ratings.*

530. An Internal-combustion Engine is an engine wherein the combustion of the fuel (Sec. 461) occurs within the cylinder of the engine. The air which is required for combustion (Sec. 464) may be mixed with the fuel before admission to the cylinder (Sec. 534), or the mixing may be effected within the cylinder Sec. (535). An amount of air in excess of that which is theoretically required for combustion is always necessary.

Explanation.—The mixture of fuel and air is ignited within the engine cylinder, usually after it has been compressed into a small volume at high pressure. Upon ignition, combustion ordinarily occurs with such rapidity that it may be considered an explosion. Thus, a large amount of energy is almost instantaneously transformed from chemical energy to heat energy. The heat energy which is liberated thereby, raises the temperature and pressure of the gaseous products of combustion. These gases, then being at an extremely high temperature, exert an enormous pressure on the piston head. This pressure on the piston, which is connected to the crank shaft through the connecting rod, causes the crankshaft to rotate. By suitable gears, belts, or other transmission devices, this rotation of the crankshaft may be utilized to drive machinery, and so do useful work. Thus, *by means of the internal-combustion engine, the chemical energy of the fuel is transformed into heat energy*, which is utilized in doing useful work. Various methods which are employed in securing this result are described in detail hereinafter in this division.

531. The Different Kinds Of Fuels Which Are Used In Internal-combustion Engines are: (1) *Gaseous fuel*, either natural gas or some kind of artificial gas such as producer gas, blast-furnace gas, or illuminating gas. Inasmuch as the artificial gases usually originate from a solid fuel (Sec. 448) the statement may be made, if considered in the broadest sense, that solid fuel may be used for operating internal-combustion engines. However, a solid fuel must ordinarily be reduced to the gaseous state before it can be effectively utilized in an internal-combustion engine. (2) *Liquid fuel*, such as gasoline, kerosene, or fuel oil. Whatever kind of fuel (Div. 13) is used, the principles involved (see Sec. 530) in transforming the chemical energy of the fuel to heat energy, and then utilizing the heat energy in doing useful work are essentially the same. However, the details of design of the engine, as shown hereinafter, are, in a measure, determined by the kind of fuel which is to be used.

532. Before Combustion Of A Fuel Can Occur, The Fuel Must Be Mixed With Air.—In order to mix the fuel with air for effective utilization in an internal-combustion engine, the fuel must first be in a gaseous state, or in a state of finely divided liquid. If there is too much air—lean mixture—or if there is insufficient air—rich mixture—the efficiency of the engine will be decreased. The best proportions of air to fuel must be determined by experiment for each individual case. In any event, the quantity of air required is greater than that (Sec. 472) which is theoretically necessary for combustion. Various methods of gasifying the fuels (Sec. 533) and mixing with air are described in the following sections.

533. The Proper Mixing Of Air With A Gaseous Fuel such as natural gas or artificial gas is a very simple matter. The air and the gas, in the proper proportions, are merely admitted (Fig. 460) to the cylinder, *C*, through the inlet valve, *V*. While passing through the valve, *V*, the mixing is effected. One method of obtaining artificial gas is described below.

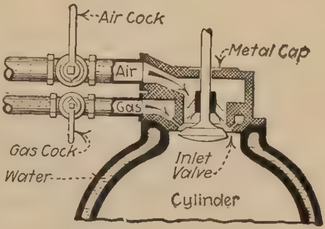


FIG. 460.—Showing method of mixing fuel and air in a gas engine.

NOTE.—AN UPDRAFT SUCTION PRODUCER-GAS POWER PLANT is illustrated in Fig. 461. The coal is fed into the top of the generator, *G*. Air which was heated in the preheater, *P*, enters the generator at its bottom. When this air comes in contact with the lower part of the fuel bed, carbon dioxide (Sec. 465) is formed. The burning of the coal to carbon dioxide supplies sufficient heat to keep the process going. As the carbon dioxide rises through the fuel bed it is reduced to carbon monoxide, which is, ordinarily, the principal combustible constituent of producer gas. Sometimes water is admitted to the generator, which, when contacting with the carbon at temperatures above 1,600° F. forms hydrogen gas and carbon monoxide ($H_2O + C = H_2 + CO$). This water, which is supplied in the form of steam, also tends to prevent clinkering. The gases which are thus formed in the generator, *G*, pass into the preheater, *P*. The hot gases give up a part of their heat in preheating the air which is supplied to *G*.

From the preheater, the gases pass through the boiler, *B*, where the steam which is admitted to the generator is formed. From *B*, the gases are piped to the scrubber, *S*. The scrubber contains wet coke. As the gases pass through the scrubber, the dust, ammonia, and tarry volatile substances are removed. A storage tank or receiver, *R*, receives the gases which come from the scrubber. The purpose of the receiver, *R*, is to prevent a sudden rush of gas through the apparatus when the gas engine, *E*, is sucking a charge, and a sudden halting of the gas flow after the admission valve is closed. The producer gas is drawn from *R* into

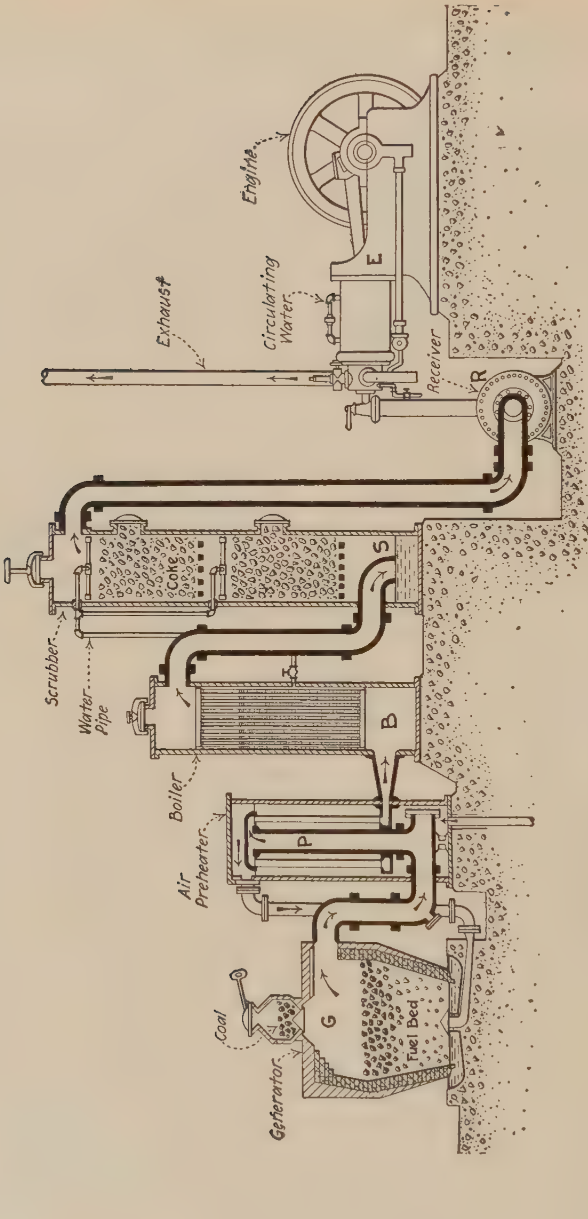


FIG. 461.—Sectional view of a typical updraft suction-producer gas-power plant

the engine, *E*, wherein it is mixed with air, and burned. The heat thus given up drives the engine (Sec. 530). The burned gases are exhausted into the atmosphere through the engine exhaust. A heat-balance chart for a producer-gas power plant is shown in Fig. 462.

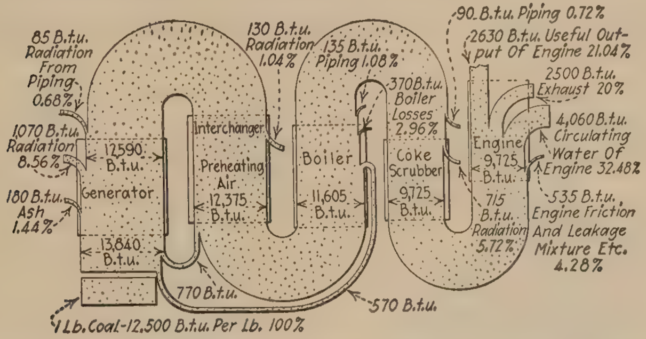

85 B.t.u. Radiation From Piping 0.68%
1,070 B.t.u. Radiation 8.56%
180 B.t.u. Ash 1.44%
12,590 B.t.u.
Generator
13,840 B.t.u.
1 Lb. Coal-12,500 B.t.u. Per Lb. 100%
130 B.t.u. Radiation 1.04%
135 B.t.u. Piping 1.08%
Interchanger
Preheating Air 12,375 B.t.u.
770 B.t.u.
Boiler
11,605 B.t.u.
370 B.t.u. Boiler Losses 2.96%
Coke Scrubber
9,725 B.t.u.
570 B.t.u.
90 B.t.u. Piping 0.72%
2630 B.t.u. Useful Output Of Engine 21.04%
2500 B.t.u. Exhaust 20%
4,060 B.t.u. Circulating Water Of Engine 32.48%
Engine
9,725 B.t.u.
715 B.t.u. Radiation 5.72%
535 B.t.u., Engine Friction And Leakage Mixture Etc. 4.28%

FIG. 462.—Heat balance diagram of a typical producer-gas power plant. The percentage values are given in terms of the total heat energy liberated by the combustion of 1 lb. of coal.

534. The Mixing Of Air With A Light-liquid Fuel, Such As Gasoline Or Kerosene, Is Usually Effected By Means Of A Carburetor (Figs. 463, 464, 465, and 466). A simplified gasoline carburetor for a portable engine is shown in Fig. 463.

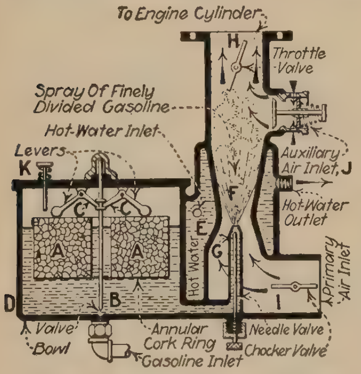


FIG. 463.—A simple gasoline carburetor.

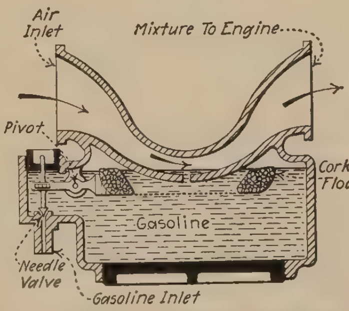


FIG. 464.—A "puddle" carburetor.

It consists of a bowl, *D*, in which the gasoline is maintained at a constant level by a *float feed-valve*. This float feed-valve consists of a cork ring, *A*, which operates the valve, *B*, through the levers, *C*. From bowl *D*, wherein the gasoline level is thus maintained practically constant, the gasoline flows through a small nozzle, *G*, around a needle valve stem. By varying the opening of this needle valve, the quantity of gasoline flowing through it may be varied. The needle-valve opening in the nozzle, *G*, is placed in a restricted passage in the air inlet, *I*.

Explanation.—During the admission or suction stroke of the piston, an air charge is drawn through this restricted passage where it attains a high velocity. The high velocity of the air through this restricted passageway results in a pressure at the needle-valve opening which is below the atmospheric pressure over the gasoline in *D*. Consequently, a fine spray of gasoline flows from the needle-valve opening and mixes with the air. The gasoline, in the form of vapor and finely divided liquid, *F*, mixes with the air and is carried into the cylinder through *H*. To further assist in vaporization, the air passage is sometimes surrounded by a chamber, *E*, through which hot water from the radiator or hot gas from the exhaust manifold is circulated. The auxiliary air inlet, *J*, is provided to vary the ratio of gasoline to air in the mixture at different engine speeds by mixing fresh air with the stream, *F*, of air and gasoline vapor. In a kerosene carburetor, the liquid in bowl, *D*, and the air are usually warmed by the

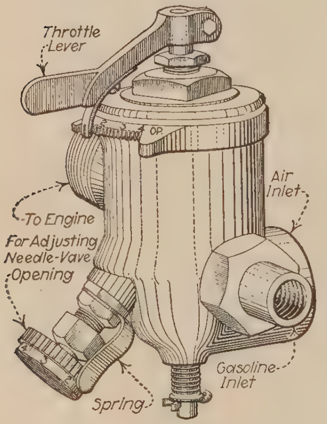


Fig. 465.

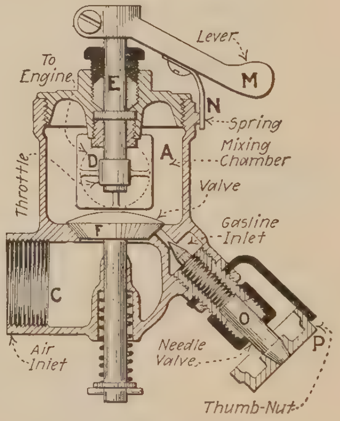


Fig. 466.

Fig. 465.—Outside view of the Lunkenheimer carburetor. (Right-hand pattern.)

Fig. 466.—Carbureting or generating valve for stationary gasoline engine. (Left-hand pattern—*The Lunkenheimer Co.* On the suction stroke, valve *F* is lifted by the suction, uncovering the gasoline port and admitting air. The air and gasoline thus admitted are mixed in the mixing chamber *A*, whence they are carried to the cylinder. The supply of gasoline is regulated by the needle valve, *O*, through the thumb-nut, *P*. The volume of the mixture which is admitted to the engine is regulated by a revolving throttle, *D*, which is operated by a lever *M*.)

hot gas from the exhaust. Stationary gasoline engines are not usually provided with a float feed-valve carburetor. For such engines a *puddle carburetor* (Fig. 464) or a carbureting valve (Fig. 466) are frequently used.

535. The Mixing Of Air With A Heavy-liquid Fuel, Frequently Called Fuel Oil is usually effected within the engine cylinder. Usually, on the suction stroke of an oil-burning engine (Sec. 547) only pure air is drawn into the cylinder. Then at the proper instant during the compression stroke, the fuel oil is sprayed into the cylinder through a properly designed fuel valve (Fig. 467) which is usually mounted in the cylinder head; see Fig. 482. The fuel valve is provided with a device called an *atomizer* (*B*, Fig. 467), the function of which is to break up the liquid fuel into small droplets so that intimate contact (Sec. 532) between the fuel and air will be provided. If the oil charge is separated into many minute particles, a greater surface area of oil is presented to the air. This results in rapid combustion. The operation of a fuel valve of the closed type is described in the note below.

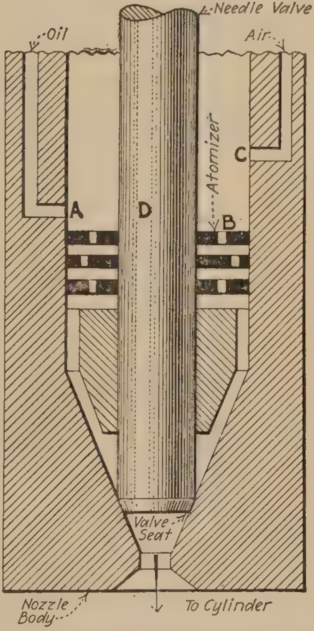


Fig. 467.—Simple fuel injection valve for high-pressure oil engine.

Note.—The Basic Principle Of A Fuel Injection Valve For High-pressure Oil-burning Engines is illustrated in Fig. 467. Fuel oil and air are pumped under high pressure into the valve through channels *A* and *C*, respectively. At the proper instant during the cycle, the needle valve, *D*, is lifted from its valve seat by means of a cam-actuated rocker. The high-pressure air carrying the oil charge with it rushes through the atomizer, *B*, and into the cylinder. The atomizer which is shown in Fig. 467 consists of three perforated discs. As the oil is forced through the tortuous passages in the atomizer discs, it is broken up into fine droplets, in which condition it is carried into the cylinder. Scarcely any two oil-engine manufacturers follow the same design in the fuel valve. However, practically all employ some such principle as that described above.

536. The Ignition Of The Fuel In Most Modern Internal-combustion Engines is effected by: (1) *An electric spark* (Figs. 468 and 469) which is caused to jump across the terminals of a spark plug (Fig. 469) in the cylinder end or which is caused by the breaking of a circuit between two contractors or "electrodes" which are located within the engine cylinder. (2) *Hot ball* or *hot bulb* (Fig. 470). In the hot-ball method of ignition, there is a ball-shaped chamber in the head end of the cylinder which is not water-jacketed. In starting the engine the ball is heated to almost a red heat by a blow-torch. The fuel valve directs the charge of fuel against this hot metal surface, whereupon ignition occurs. Then after the engine is started, the ball is maintained at a red heat by the heat of the combustion. (3) *Compression.* In the compression method of ignition the pure air which is drawn into the cylinder on the suction stroke (Sec. 547) is, at the end of the compression stroke, at such a high temperature that it ignites the fuel charge as soon as the fuel is admitted to the cylinder.

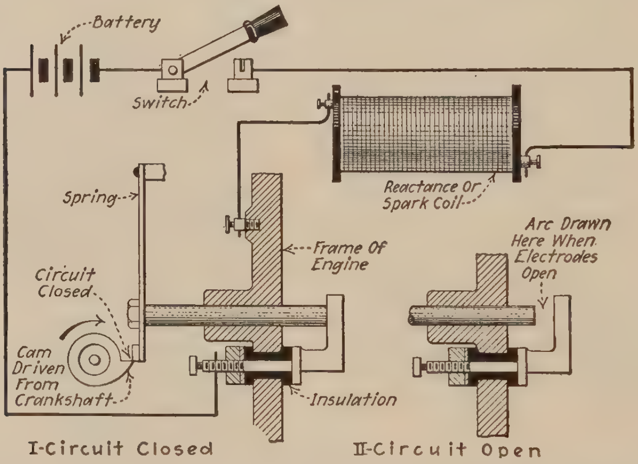


Fig. 468.—Diagram of make-and-break (electric) ignition system. This system has the one advantage of low cost and therefore is used chiefly on relatively cheap engines.

NOTE.—APPLICATIONS.—In general, the electric spark is used for igniting the fuel in gas, gasoline, and kerosene engines; the hot-ball method for low- and medium-pressure (Sec. 546) oil engines; and the compression method for medium- and high-pressure oil engines.

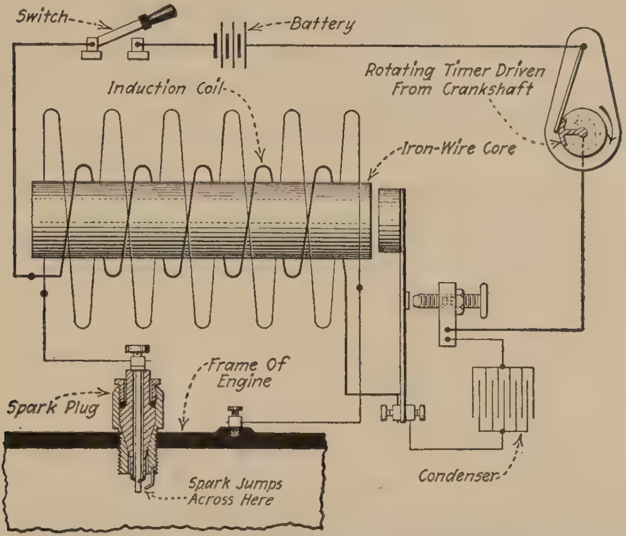


FIG. 469.—Diagram of high-tension (jump-spark) ignition system. This system is generally more reliable than the low-tension system (Fig. 468) and, though more expensive, is gradually superceding it.

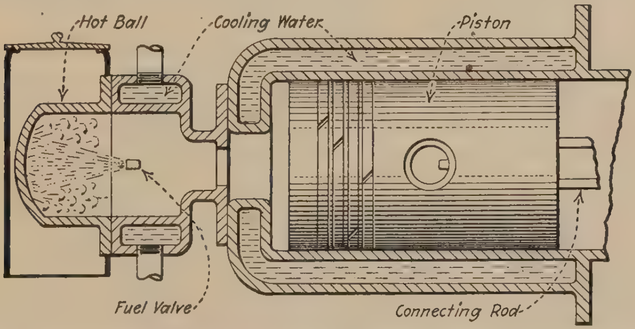


FIG. 470.—Illustrating the hot-ball method of ignition for low-pressure oil-burning internal-combustion engines.

537. The Three General Methods Of Governing Internal-combustion Engines are: (1) *The hit-and-miss method.* (2) *Quantitative or constant-quality governing.* (3) *Qualitative or* *constant-quantity governing.* The hit-and-miss method is, from the standpoint of fuel economy, the most economical of the three methods. However, it is practical only for small engines where close speed regulation is not required. Some internal-combustion engines of the modern types employ a combination of the quantitative and qualitative methods of governing which is relatively simple and which provides a regulation, from no load to full load, of about 2 or 3 per cent. Each of these methods are briefly described in the notes below.

NOTE.—THE HIT-AND-MISS METHOD OF GOVERNING INTERNAL-COMBUSTION ENGINES consists in causing the engine to fail to take in a charge of fuel as long as the speed is too high. This is accomplished by having the governor so connected that as long as the speed is too high the inlet valve is held closed. In some engines, while the inlet valve is held closed the exhaust valve is held open and in other engines both the inlet and exhaust valves are held closed during the miss cycle. This method of governing is economical because the ratio of air to fuel in the mixture is constantly maintained at the most desirable value and a "full" charge of mixture is admitted whenever the fuel valve is open during a suction stroke (Sec. 540). However, in a four-stroke-cycle engine (Sec. 540), if the engine fails to take in a fuel charge it must make three more strokes before it has the opportunity to take in another fuel charge. In the meantime, the speed may have dropped too low. Relatively large flywheels are required for engines which employ this method of governing. The hit-and-miss method of governing is used for small gas and gasoline engines where close speed regulation is unimportant, as for example for engines for pump and concrete-mixer drives.

NOTE.—IN THE QUANTITATIVE METHOD OF GOVERNING, the quantity of the charge is varied but the ratio of air and fuel in each charge remains constant. This method of governing may be effected by throttling, or by cutting off the fuel supply before the end of the suction stroke. Cut-off governing is not much used because of the complexity of the valve gear which is required. The objection to quantitative governing is that, as the load decreases, less mixture is drawn into the cylinder per cycle and the compression pressure decreases. Consequently, at light loads the efficiency is materially less than at full load. The quantitative method of governing is used for gas and gasoline engines in those services where very close speed regulation is required and where heavy flywheels would be objectionable—as, for example, in engines which drive alternating-current generators in parallel operation, and in automobile-truck, tractor, and large marine engines. Quantitative control is also employed where engines must be "governed" (by hand) to run at various speeds, as in automobiles, aeroplanes, and motor boats.

NOTE.—THE QUALITATIVE METHOD OF GOVERNING consists of varying the quality of the mixture—ratio of fuel to air in the charge—while the quantity of the charge remains nearly constant. The objection to this method of governing is that, at light loads the ratio of the fuel to the air is so small that sometimes the fuel may fail to ignite. Then, the fuel in the charge which did not fire is wasted through the exhaust. Also a "weak" mixture burns very slowly, giving very little pressure on the beginning of the expansion stroke and, in extreme cases, the fuel is not all burned even at the end of the stroke. The qualitative method of governing, in improved form, is used for practically all oil engines—low-pressure, semi-Diesel, and Diesel.

538. Internal-combustion Engines May Be Classified According To The Number Of Strokes Per Cycle as: (1) *Two-stroke-cycle engine*, Fig. 471, sometimes called *two cycle*—wherein a complete cycle of events occurs for each two strokes of the piston. (2) *Four-stroke-cycle engine* (Fig. 472)—sometimes called *four cycle*—wherein a complete cycle of events occurs for each four strokes of the engine. Engines of each

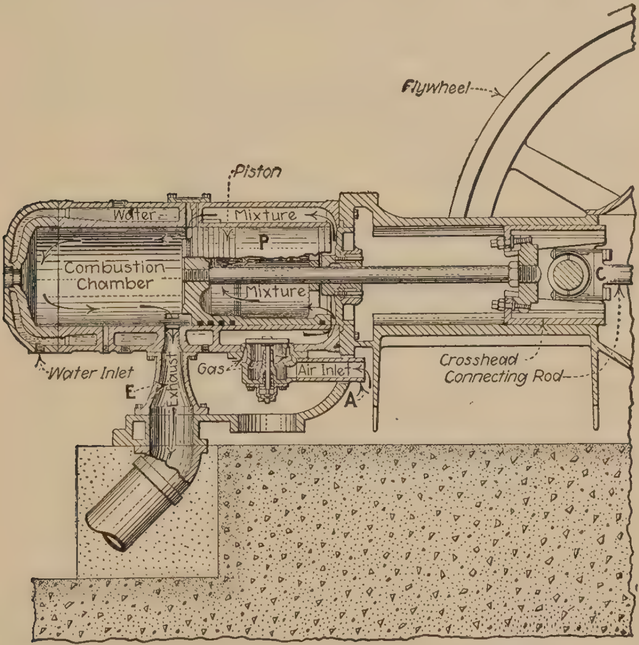


FIG. 471.—Longitudinal section of Bessemer two-stroke-cycle gas engine.

of these types are used. Each gives good results in the service (Sec. 541) for which it is suitable. The cycles of events for engines of each type are described in the following sections.

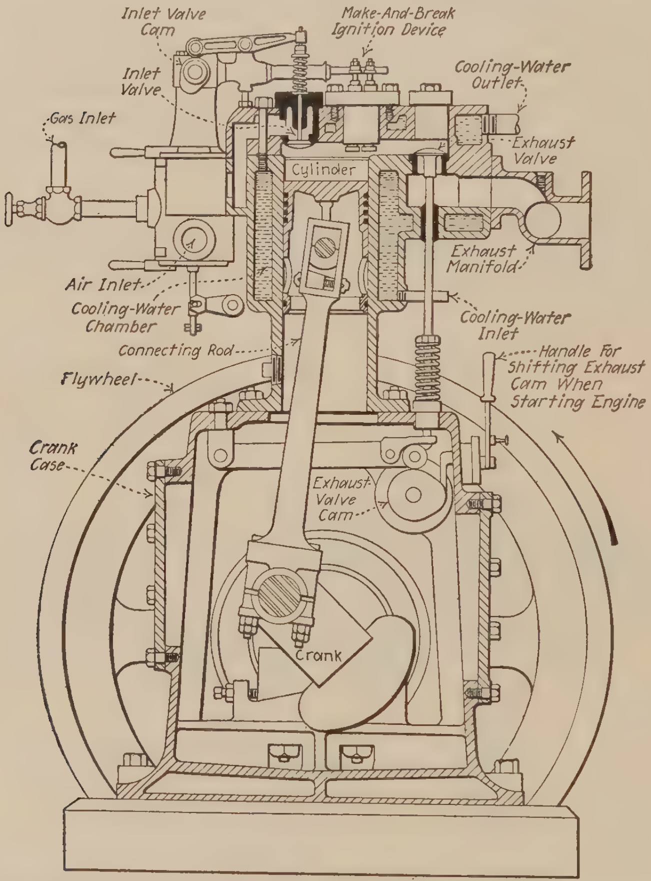


Fig. 472.—Vertical section of a single-acting four-stroke-cycle, vertical gas engine.

Note.—Practically All Internal-combustion Engines Must Be Started From Some Outside Source Of Power.—The power for starting large engines is generally provided by compressed air. Small engines are usually started by hand, or by an electric motor driven from storage batteries.

539. A Two-stroke-cycle Internal-combustion Engine is illustrated in Fig. 471. Engines of this type have no inlet or exhaust valves. The gases are admitted and exhausted through ports in the cylinder which are covered and uncovered at the proper time during the piston travel. Some two-stroke-cycle engines are made with two ports, and some are made with three ports. The operation of a single-cylinder two-port, two-stroke-cycle gasoline engine is explained below.

Explanation.—Figure 473 represents a piston, *A*, within the cylinder, *B*, of a two-port, two-cycle gasoline engine. The piston is connected to a crank, *D*, by means of a connecting rod, *C*, so that continuous rotation of the crank imparts a reciprocating motion to the piston. Or conversely, a reciprocating motion of the piston will cause a rotating motion of the shaft.

Assume that the piston is in the position shown in Fig. 473-*I* and that crank *D* is rotated, in the direction indicated by the arrow, by some outside source of power (Sec. 538). This causes the piston to move upward to the position shown at *II*. This upward movement of the piston—which is called the *crankcase suction stroke*—increases the volume of the gases in the crank case, thereby decreasing the pressure within the crankcase below that of the atmosphere. Consequently, the atmospheric pressure on the outside of the crankcase causes air to enter the crankcase through the carburetor, *G*.

As the air passes through the carburetor (Sec. 534) it picks up and vaporizes a quantity of fuel which is mixed with and carried into the crankcase by the air. As the crank is rotated further by the outside source of power, the piston is moved downward to the position shown at *III*. This downward movement of the piston—which is called the *crankcase compression stroke*—compresses the air-and-fuel mixture which is in the crankcase so that its pressure is something above that of the atmosphere. A check valve (not shown in illustration) prevents the fuel charge from being forced out through the carburetor.

Therefore, when the inlet port (*E*, Fig. 473-*III*) is uncovered by the downward movement of the piston, the air-and-fuel mixture, being at a higher pressure than the gases in the cylinder, passes through *E* into the cylinder. As the fuel charge—that air-and-fuel mixture—passes into the cylinder, it is deflected upward toward the top of the cylinder by the baffle, *I*. This prevents, to a large extent, the escape of the fuel charge through the exhaust port *F*, which at this time is also uncovered and open to the atmosphere.

Further rotation of the crank moves the piston upward to the position shown in *IV*. This upward movement of the piston—which is called the *cylinder compression stroke*—covers the ports *E* and *F* and compresses the fuel into the small clearance volume at the top of the cylinder. At the same time that the piston moves upward on the cylinder compression stroke, another fuel charge is drawn into the cylinder in the same manner as it was in the crankcase suction stroke explained above. While the fuel is compressed in the upper part of the cylinder (Fig. 473-*IV*), an electric "spark" or arc is made to jump between the electrodes or "points" of the spark plug. See Sec. 536 on ignition. This ignites the fuel.

After ignition combustion of the fuel occurs so rapidly that it may be termed an explosion. The chemical energy which is liberated as heat by the combustion raises the temperature and pressure of the products of combustion, thereby exerting a great downward force on the piston. The downward force on the piston causes it to move downward. The downward movement of the piston which is caused by the pressure of the heated products of combustion is called the *work stroke*. This downward

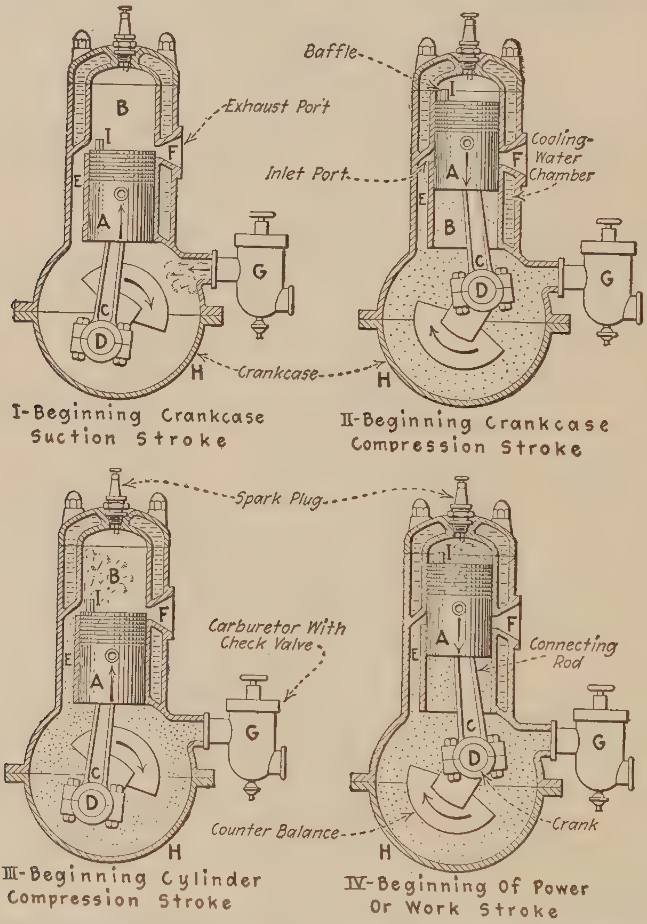

B
I
A
E
F
C
D
G
H
Exhaust Port
Baffle
Inlet Port
Cooling Water Chamber
Crankcase
I-Beginning Crankcase Suction Stroke
II-Beginning Crankcase Compression Stroke
Spark Plug
Carburetor With Check Valve
Connecting Rod
Counter Balance
Crank
III-Beginning Cylinder Compression Stroke
IV-Beginning Of Power Or Work Stroke

Fig. 473.—Illustrating the operation of a two-port, two-stroke-cycle gasoline engine.

motion of the piston is, through the connecting rod and the crank, transmitted to the shaft and causes it to rotate. Thus, the chemical energy of the fuel is transformed into heat energy which is in turn transformed into mechanical work of rotating the engine shaft.

During this work stroke the fuel charge which was drawn into the crankcase during the cylinder compression stroke is compressed in the crankcase. About the time the piston completes the work stroke the exhaust port, F (Fig. 473-*III*), is uncovered and the burned gases begin to pass out through it to the atmosphere. A little later in the work stroke the inlet port, E, is uncovered and the fuel charge which is compressed in the crankcase passes into the cylinder and expels the remainder of the burned gases. This expulsion of the burned gases is called *scavenging*.

The fuel charge which has just passed into the cylinder is compressed on the next upward stroke of the piston. The work which is required for this second cylinder compression stroke is done by the energy which was stored in the flywheel during the first work stroke. From this point on, the cycle of operations is continually repeated, each event of the cycle occurring as described above. However, after the engine is running on its own power, the work stroke and the crankcase compression stroke occur simultaneously; also, the cylinder compression stroke and the crankcase suction stroke occur simultaneously.

540. The Operation Of A Four-stroke-cycle Internal-combustion Engine is explained below. For the purpose of explaining the operation only one cylinder is shown. However, four-stroke-cycle engines are frequently made with more than one cylinder.

Explanation.—Figure 474 represents a piston, P, within the cylinder, G, of a four-stroke-cycle gas engine. The piston is connected to a crank, C, by means of the connecting rod, R, so that continuous rotation of the crank imparts a reciprocating motion to the piston. Or conversely, a reciprocating motion of the piston will cause a rotating motion of the crank. The inlet valve, A, and the exhaust valve, E, are controlled through the cams and push rods by gears Y and X. Gears Y and X are driven by a third gear T which is mounted on the crankshaft. The ratio of the number of teeth in gears X and Y to the number on T is 2 : 1. Consequently, for each revolution of T, gears X and Y make ½ of a revolution.

Assume that the piston P and the gears X and Y are in the positions as shown in Fig. 474, and that the crank, C, is rotated by an outside source of power (see note under Sec. 538) in the direction indicated by the arrow. The piston moves downward. The increase in the cylinder volume above the piston decreases the pressure therein and causes a charge of fuel-and-air-mixture to be drawn into the cylinder through the inlet valve *A*. This downward movement of the piston is called the *suction stroke* or *admission stroke.* By the time the suction stroke is completed (Fig. 475), the inlet valve is closed.

Further rotation of the crank by the outside source of power causes the piston to move to the top of the cylinder (Fig. 476) thus compressing the charge, which is entrapped therein, into the small clearance volume at the top of the cylinder. This is called the *compression stroke.* When the piston is in this position, the compressed charge is ignited (Fig. 476) by an electric "spark" or arc which is made to jump between the electrodes or "points" of the spark plug. The combustion of the fuel follows the ignition. This combustion is so rapid that it may be termed an explosion. The heat of combustion raises the temperature, and consequently the pressure, of the gaseous products of combustion. The force which is thus exerted on the piston head by the high-pressure gases causes it to move downward (Fig. 476). This is called the *work stroke.* The downward movement of the piston during the work stroke imparts a rotating motion to the crankshaft.

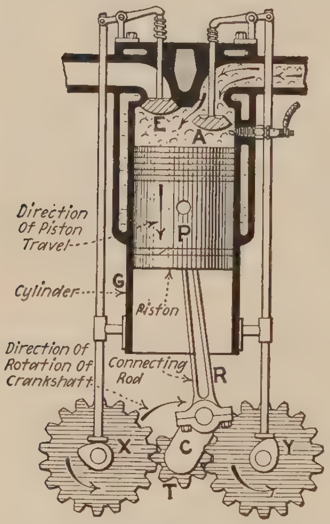

E
A
Direction Of Piston Travel
P
Cylinder
G
Piston
Direction Of Rotation Of Crankshaft
Connecting Rod
R
X
C
Y
T

FIG. 474.—Four-stroke-cycle gas engine. (Beginning of admission stroke.)

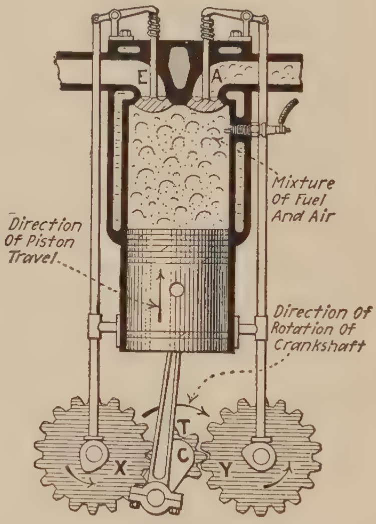

E
A
Mixture Of Fuel And Air
Direction Of Piston Travel
Direction Of Rotation Of Crankshaft
T
C
X
Y

FIG. 475.—Four-stroke-cycle gas engine. (Beginning of compression stroke.)

Thus, the chemical energy of the fuel is transformed into heat energy within the engine cylinder, and the heat energy is transformed into work of rotating the shaft. At the completion of the work stroke, the cam on gear *X* opens the exhaust valve, *E*, so that further rotation of the shaft moves the piston upward and expels the gases from the cylinder through

E and the exhaust manifold (Fig. 477). This is called the *exhaust stroke.* At the completion of the exhaust stroke, valve *E* closes.

Further rotation of the shaft moves the piston downward on the suction stroke of the next cycle. A four-stroke cycle may be said to begin with the suction stroke and to end with the exhaust stroke. The work which is required to perform the exhaust stroke of one cycle and the suction and compression strokes of the succeeding cycle is, in a single-cylinder four-stroke-cycle engine, done by the energy which was stored in the flywheel as kinetic energy during the previous work stroke. Thus, in starting the engine, the outside source of power which is used to rotate the crank shaft may be removed after the first explosion occurs.

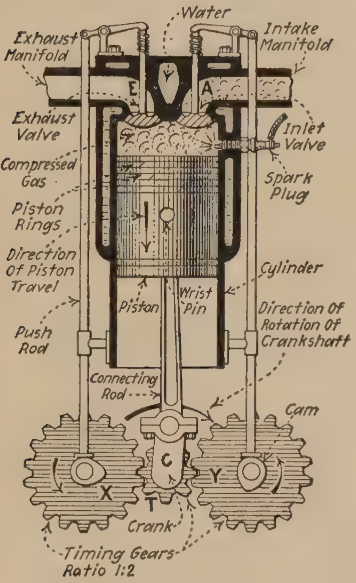


FIG. 476.—Four-stroke-cycle gas engine. (Fuel and air, having been compressed, is ignited by electric spark. Beginning the first downward or work stroke of the cycle.)

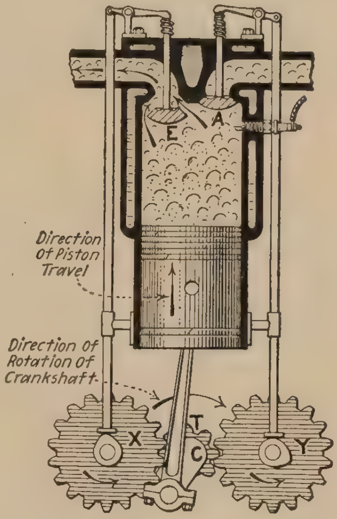

E
A
Direction Of Piston Travel
Direction Of Rotation Of Crankshaft
X
T
C
Y

FIG. 477.—Four-stroke-cycle gas engine. (Work which was begun in Fig. 476 is completed when piston reaches bottom of stroke. Exhaust-valve has opened and piston is traveling upward, beginning the first upward or exhaust stroke of the cycle.)

541. Internal-combustion Engines May Be Designed To Operate On Either The Four-stroke Or Two-stroke Cycle.—Indicator diagrams from low-pressure gas engines operating on the two- and the four-stroke-cycle are shown in Figs. 478

and 479. From a comparison of these two indicator diagrams, it might be thought that an engine which operates on the two-stroke cycle would be preferable to one operating on the four-stroke cycle, because for the same number of revolutions the two-stroke cycle engine would give twice as many explosions as would the four-stroke cycle engine, and hence would appear to develop twice the power. However, for the same size cylinder and the same number of revolutions per minute, a two-stroke-cycle engine only develops from 1.3 to 1.7 times the power of a four-stroke cycle engine. This is partially due to imperfect scavenging of the burned gases in the two-stroke-cycle engine and to a slight loss of fuel which escapes with the burned gases during scavenging. The simplicity and low maintenance cost of two-stroke-cycle engines very often, especially for small-capacity installations, make these engines more desirable than four-stroke-cycle engines. Two-stroke-cycle engines are also used because their weight per horsepower is considerably less than the weights of four-stroke-cycle engines of equal power. For this reason they are widely used as marine engines.

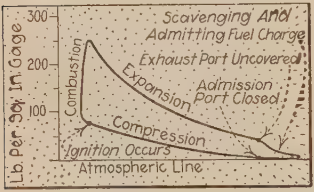


Fig. 478.—Cylinder indicator diagram of a two-stroke-cycle gas engine.

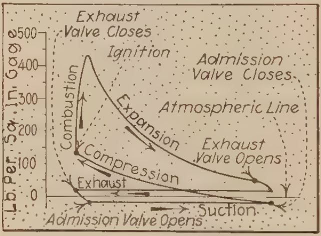


Fig. 479.—Indicator diagram of a four-stroke-cycle gas engine.

Note.—Two-stroke-cycle Engines Are Employed where small weight, small space and low first cost are more important factors than maximum operating efficiency. They are frequently, though not always, used in motor boats, farm service, and in the oil fields.

Note.—Four-stroke-cycle Engines Are Employed where maximum efficiency is of the greater importance than weight, space occupied, and first cost. Thus, they are generally, though not always, used for automobiles, aeroplanes, tractors, and electric-central station prime movers.

542. Table Showing Classification Of Internal-combustion Engines According To Compression Pressure. (Marks, "Mechanical Engineers' Handbook.")

Pressure classification	Fuel used	Type of engine	Compression pressure in lb. per sq. in., gage	
			Range	Average
Low	Fuel oil	Injected into hot bulb before compression	45	45
	Kerosene	Vaporized before entering cylinder	45 to 85	65
	Gasoline	Automobile	45 to 95	65
	Kerosene	Hot bulb, 250 to 500 r.p.m.	30 to 75	60
	Gasoline	Stationary	60 to 105	70
	Water gas	Small gas engines, very few large	75 to 105	90
	Coal gas	Small gas engines, very few large	75 to 120	100
Medium	Coke-oven gas	Large engines (in Germany)	105 to 135	120
	Natural gas	Medium and large engines	75 to 160	120
	Producer gas	Both large and small engines	100 to 160	130
	Alcohol	Vaporized before entering cylinder	120 to 210	150
	Blast-furnace gas	Largest built	120 to 190	155
	Fuel oil	Injected after compression—semi-Diesel	255	255
High	Fuel oil	Diesel engine	510	510

543. Internal-combustion Engines May Be Classified According To The Compression Pressure (Table 542) as follows: (1) *Low pressure.* (2) *Medium pressure.* (3) *High pressure.* Those low-pressure engines (Table 542) which use gas and light liquid fuels such as gasoline, kerosene, and alcohol, are very similar in operation to the medium-pressure engines using the same fuels. The principal difference is in the compression pressures. In the low, medium, and high-pressure engines which use fuel oil, there is a difference in the pressures, the method of ignition, and in the cycle on which the engine operates, ordinarily the Otto cycle or the Diesel cycle (Sec. 422 and 424). Engines of each of these types are described in the following sections.

NOTE.—THE COMPRESSION PRESSURE OF AN INTERNAL-COMBUSTION ENGINE is the pressure (Sec. 5) which the fuel charge exerts on the piston just before ignition occurs. It is usually measured in pounds per square inch.

NOTE.—IT IS MECHANICALLY POSSIBLE TO BUILD INTERNAL-COMBUSTION ENGINES in nearly any combination of the following arrangements: (1) *Two-stroke or four-stroke cycle.* (2) *Single- or multi-cylinder.* (3) *Single- or double-acting.* (4) *Horizontal, vertical or inclined.* (5) *Simple or compound.*

544. Low-pressure Internal-combustion Engines Which Use Gas Or Light Liquid Fuels Usually employ some form of mixing valve (Sec. 533) or carburetor (Sec. 534) for mixing the fuel and air. The mixture of air and fuel is drawn into the engine on the suction stroke and is compressed on the compression stroke. At the beginning of the compression stroke the volume of the fuel and air is equal to the piston displacement plus the clearance volume. At the end of the compression stroke the volume of the fuel and air is equal to the clearance volume. Consequently, the pressure and temperature of the charge depend, among other things, upon the size of the clearance volume as compared with the piston displacement. If the compression pressure were carried too high, the temperature would rise sufficiently to ignite the charge before the end of the compression stroke. For this reason, those internal-combustion engines which compress the fuel must operate at low or medium pressures (Table 542) of from about

45 to 190 lb. per sq. in., gage. At the end of the compression stroke the fuel charge is ignited, usually, by an electric spark (Sec. 536). Gasoline and kerosene engines are particularly well adapted for small and medium-capacity portable installations. Gas engines are frequently used in those localities where the fuel is cheap.

545. In Low-pressure Oil Engines (Fig. 480) the kerosene or fuel oil is sprayed onto the vaporizer (See also Fig. 470) or hot plate *O* by the fuel pump, *F*, immediately after the completion of the exhaust stroke. During the compression stroke the oil is vaporized and forced into the hot ball *G* and finally ignited. The maximum compression pressure is about 50 lb. per sq. in. gage. The operation of the engine shown in Fig. 480 is similar to that described in Sec. 544. Low-pressure oil engines are well adapted for low-capacity installations where it is desired to use a cheap fuel. They are simple in construction, very reliable and require but little attention. Consequently the first cost and operating costs are low.

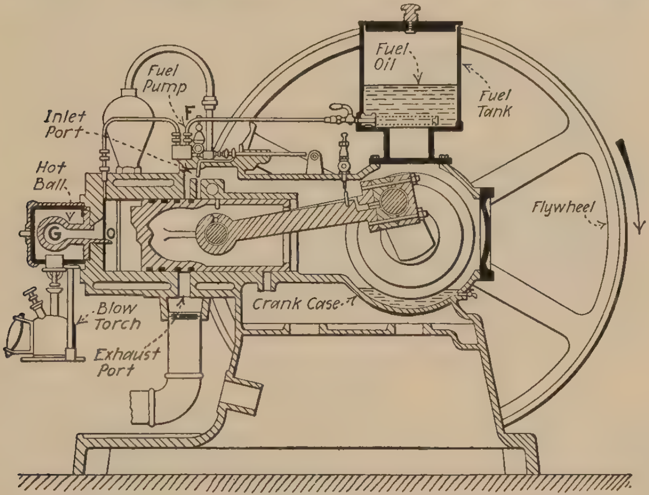


Fig. 480.—*Meitz and Weiss* low-compression, two-stroke-cycle oil engine.

546. The Semi-Diesel Oil Engine Is A Medium-pressure Engine (Fig. 481). In the semi-Diesel engine a maximum compression pressure of about 250 lb. per sq. in. gage occurs near the end of the compression stroke, at which time the fuel oil is injected into the cylinder by compressed air. Ignition is usually effected by a hot ball (Sec. 536) just as in the low-pressure oil engine (Sec. 545). In some semi-Diesel engines ignition is effected by the compression pressure in conjunction with a hot cup. The efficiency of the semi-Diesel engine is slightly lower than that of the true Diesel engine and generally higher than that of the low-compression oil engine. However, the relatively simple construction, low first cost, and low operating charges of the semi-Diesel engine often justify its use in those installations of small and medium capacity where the services of a highly skilled operator (which is usually required for Diesel engines) would be uneconomical.

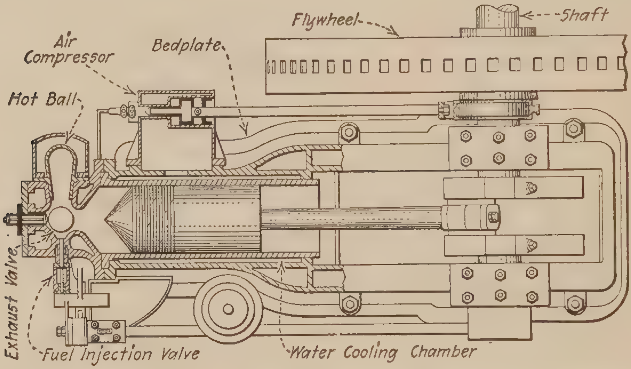


FIG. 481.—Horizontal section of a *De La Vergne* four-stroke-cycle, horizontal, semi-Diesel engine.

547. The High-pressure Internal-combustion Engine Is Typified By The Diesel Engine (Figs. 482 and 483). In the four-stroke-cycle Diesel engine (Fig. 483), the charge of fresh air, which is drawn into the engine through the air inlet value, *I*, during the suction stroke, is compressed to about 500 lb. per sq. in. gage at the end of the compression stroke. The temperature of the fresh-air charge at the end of the compression stroke is about 1,000° F. At about the end of the compression stroke, the fuel and air injection values are opened and the compressed injection air, which is at a pressure of from 700 to 900 lb. per sq. in., atomizes and forces a charge of fuel oil into the cylinder. Upon contact of the atomized fuel oil with the high-temperature fresh air, ignition occurs, and the combustion continues until the fuel supply is cut off.

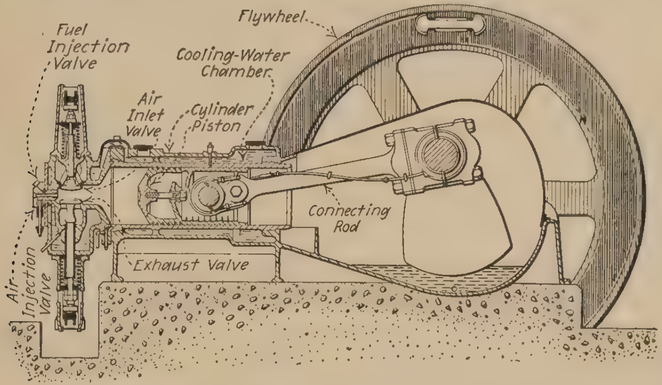


FIG. 482.—Longitudinal section through an *Allis-Chalmers* Diesel engine.

Governing is usually effected by regulating the amount of fuel injected. Diesel engines are the most efficient heat engines (Table 551) which have so far been developed. They are very heavy and require a heavy foundation. They are relatively complicated and require the attendance of a highly skilled operator. They are particularly well adapted for medium- and high-capacity installations in those locations

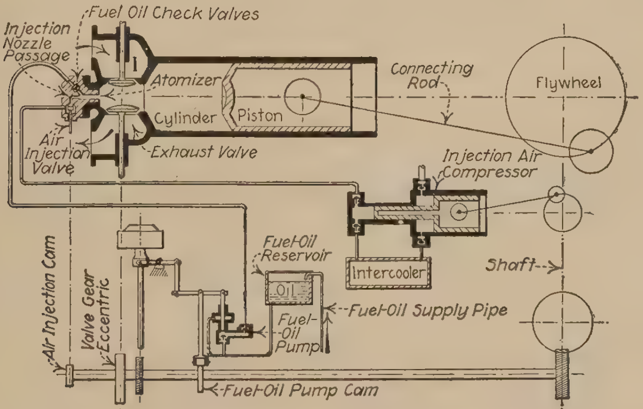


FIG. 483.—Schematic arrangement of an *Allis-Chalmers* Diesel engine.

which justify the use of a liquid fuel. Diesel engines are being extensively used in the marine service where the available engine space and fuel-storage space is a minimum. Modern Diesel-engine governing provides speed regulation which is sufficiently close that they may be used to drive alternators which are connected in parallel.

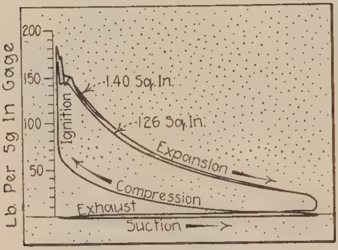


Fig. 484.—Typical full-load indicator card of a low-pressure four-stroke-cycle oil-engine.

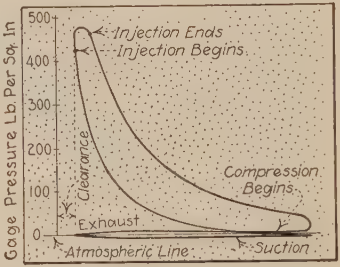


Fig. 485.—Typical indicator card of a Diesel four-cycle engine.

548. Practically All Internal-combustion Engines Operate Either On The Otto Or On The Diesel Cycle (Div. 12) or upon a modified combination of these two gas cycles. Indicator diagrams for engines of the various types are shown in Figs. 478, 479, 484, 485 and 486. In those engines wherein the air and fuel are mixed before admission to the cylinder (Figs. 478 and 479) and in the low-pressure oil engine (Fig. 484 and Sec. 545), combustion occurs almost instantaneously after ignition. Consequently, the piston movement during the combustion period is practically negligible. That is, the heat is added at a constant volume. This is one of the characteristics of the Otto gas cycle (Sec. 422). In the Diesel engine (Sec. 547) combustion occurs as long as the fuel is being sprayed into the cylinder. Thus, in the Diesel engine, the rate of fuel admission is so timed with respect to the piston travel that heat is added (Fig. 485) at practically constant

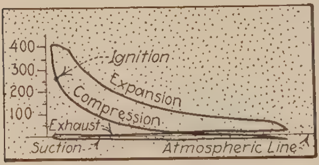


Fig. 486.—Indicator card of a four-stroke cycle semi-Diesel engine.

pressure. Usually, in the semi-Diesel engine, a part of the heat is added (Fig. 486) at constant volume and a part is added at constant pressure.

549. Tests Of Internal Combustion Engines are made in a manner which is very similar to that of steam engines (see the author's STEAM-ENGINE PRINCIPLES AND PRACTICE). The brake horsepower may be determined by means of a brake or electrically. The indicated horsepower may be determined by the following formula:

$$\mathbf{P} = \frac{PLAN}{33{,}000} \qquad \text{(horsepower)} \tag{351}$$

Wherein: $\mathbf{P}$ = the indicated horsepower. L = length, in feet, of piston travel or stroke. A = the net area, in square inches, of the piston. N = number of work strokes per minute. P = the mean effective pressure, in pounds per square inch, as determined from the indicator card (Sec. 503). In determining the mean effective pressure from the indicator card of a four stroke cycle gas engine, the area bounded by the exhaust and suction stroke lines (Fig. 484) represents negative work and must be subtracted from the area bounded by the compression and expansion stroke lines. Compare For. (351) with similar For. (343) for a steam engine.

550. The Theoretical Thermal-efficiency Of Internal Combustion Engines is much greater than that of steam engines. Also, as shown in Table 551, the *overall thermal efficiency* of internal combustion engines is greater than that of steam engines. The difference in the actual thermal efficiencies of engines of these two different types results from the different pseudo cycles (Sec. 402) upon which they operate, and in the difference in temperatures which are attained at those points on the cycles which determine the thermal efficiencies. The high actual thermal efficiency of an internal-combustion engine is due, largely, to the high pressure which is attained at the end of the compression stroke. See also the note below.

NOTE.—THE MAXIMUM POSSIBLE THERMAL EFFICIENCY OF ANY HEAT ENGINE operating between two given temperature limits, would result if the engine operated on the Carnot cycle (Sec. 412). The thermal efficiency of an engine operating on the theoretical Carnot cycle is given by the expression $(T_1 - T_2) \div T_1$, wherein T_1 and T_2 are, respectively,

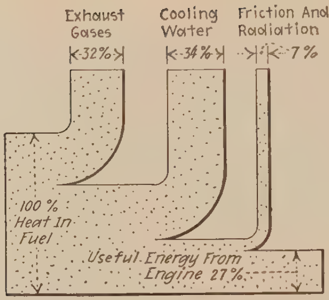


FIG. 487.—Heat balance in gas-engine plant where the fuel is purchased in the gaseous state.

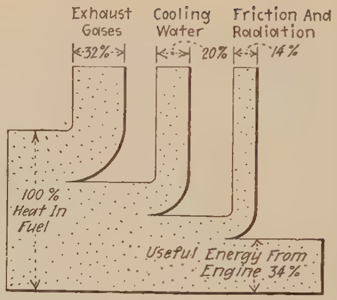
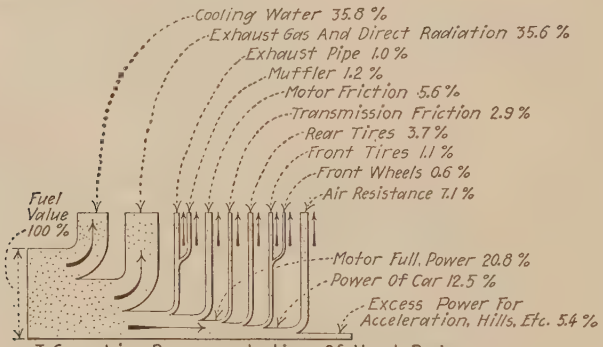
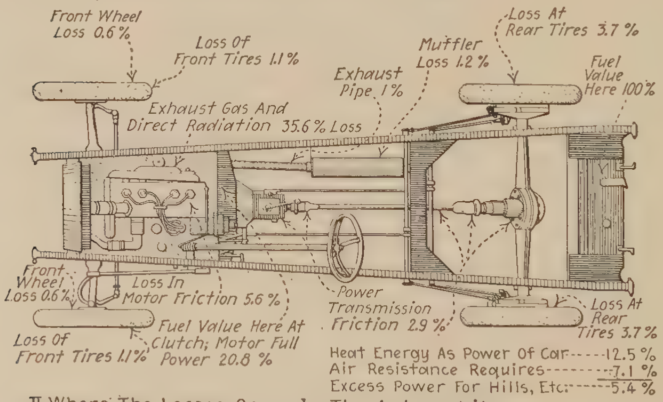


FIG. 488.—Heat balance in Diesel-engine plant.



I-Graphic Representation Of Heat Balance


Front Wheel Loss 0.6 %
Loss Of Front Tires 1.1 %
Exhaust Gas And Direct Radiation 35.6 % Loss
Exhaust Pipe 1 %
Muffler Loss 1.2 %
Loss At Rear Tires 3.7 %
Fuel Value Here 100 %
Front Wheel Loss 0.6 %
Loss In Motor Friction 5.6 %
Loss Of Front Tires 1.1 %
Fuel Value Here At Clutch; Motor Full Power 20.8 %
Power Transmission Friction 2.9 %
Loss At Rear Tires 3.7 %
Heat Energy As Power Of Car-----12.5 %
Air Resistance Requires---------7.1 %
Excess Power For Hills, Etc.------5.4 %

II-Where The Losses Occur In The Automobile

FIG. 489.—Plan view of five-passenger four-cylinder automobile chassis showing how the heat units liberated by the combustion of the fuel in the engine cylinders are utilized, and what proportion is actually employed in driving the car when it is run at a rate of 40 mi. per hr. on high gear.

the maximum and minimum absolute temperatures which are attained during the cycle. In a steam engine operating at a steam pressure of 250 lb. per sq. in., gage, the maximum temperature is about 400° F. In internal-combustion engines, the maximum temperature varies from 2,200 to 3,000° F. The minimum temperature for an engine of either type operating on the Carnot cycle would be the atmospheric temperature, which may be taken as 70° F.

Assume a value of 2,500° F. as the maximum temperature which is attained in an internal-combustion engine. Then, by reducing the values above to absolute temperatures and substituting in the above expression $(T_1 - T_2) \div T_1$, the thermal efficiency of the internal-combustion engine would be: $[(2{,}500 + 460) - (70 + 460)] \div (2{,}500 + 460) = 0.82$, or about 82 *per cent.* and that of the steam engine would be: $[(400 + 460) - (70 + 460)] \div (400 + 460) = 330 \div 860 = 0.383$, or about 38 *per cent.* However, because of theoretical and practical considerations, such high thermal efficiencies are never realized. The heat balance diagrams of Figs. 487, 488 and 489 show the percentage of the heat energy of the fuel which is transformed into work by internal-combustion engines of various types, and also the percentages of the heat which is lost through various channels.

551. Table Of Heat Consumption and Thermal Efficiencies Of Different Types Of Prime Movers At Continuous Full Load.

(*Gov. Bull.* 156, "The Diesel Engine, Its Fuel And Its Uses.")

Type of prime mover	Heat consumption per b.hp.-hr. in B.t.u.	Overall thermal efficiencies
Non-condensing steam engine	40,000–28,000	6.3– 9.1
Condensing engine using superheated steam	28,000–16,500	9.1–15.4
Locomobile engine with superheated steam and reheater, condensing	17,000–15,200	14.9–16.7
Steam turbine, superheated steam, 200 to 2,000 hp	24,000–15,500	10.6–16.2
Steam turbine, superheated steam, 2,000 to 10,000 hp	15,500–14,000	16.2–18.1
Producer-gas engine, suction producer	14,000–11,200	18.1–22.7
Gas engine without producer	10,400– 9,300	24.4–27.5
Diesel engine	8,000– 7,200	32.0–35.3

NOTE.—THE THERMAL BRAKE EFFICIENCY OF AN INTERNAL COMBUSTION ENGINE (Table 551), expressed as a decimal, may be obtained by the following formula:

$$(352)\quad \textit{Thermal brake eff.} = \frac{2{,}545 \times (\textit{Brake horsepower developed})}{\begin{pmatrix}\textit{No. of unit meas-}\\ \textit{ures of fuel con-}\\ \textit{sumed per hr.}\end{pmatrix} \times \begin{pmatrix}\textit{Heat value, in}\\ \textit{B.t.u. of a unit}\\ \textit{measure of fuel.}\end{pmatrix}}$$

For liquid and solid fuels, the unit measure is usually the pound. For gaseous fuels, the unit of measure is usually the cubic foot at a temperature of 62° F. and at a pressure of 30 in. of mercury.

EXAMPLE.—In a test of a certain Diesel engine, 492 b hp. was developed. The rate of fuel consumption during the act was 221 lb. per hr. The heating value of this fuel oil was 19,100 B.t.u. per lb. What was the thermal brake efficiency? SOLUTION.—Substituting in For. (352), *the thermal brake efficiency* = (2,545 × 492) ÷ (221 × 19,100) = 0.296, or 29.6 *per cent.*

552. Internal-combustion-engine Cylinders Must Be Provided With Some Means To Augment Cooling.—If some method of cooling were not provided, the high temperatures which exist within the engine cylinders (Sec. 550) would render the engine inoperative in a very short time. Internal-combustion engines are usually either *water-cooled* (Fig. 490) or *air cooled* (Fig. 491). In a water-cooled engine, the water is circulated through cooling chambers (Figs. 480, 481 and 482) which surround the cylinder. In some of the large-capacity engines, the cylinder head, the valves, and the piston are also artificially cooled. The water, after being heated in the cooling-water chambers, is usually cooled by some external means such as a tank, hopper, cooling tower, or a radiator. In some instances, the heat which is transmitted to the cooling water is utilized for warming buildings or for doing mechanical work. The cooling-water circulation in large-capacity engines is usually provided by a small centrifugal pump, (Fig. 490) whereas, in small-capacity engines the cooling water is circulated by

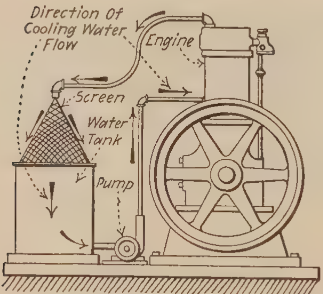


FIG. 490.—Gas engine provided with small pump and cooling tower for circulating and cooling the cooling-water. The water is cooled by evaporation (Sec. 300) in flowing over the screen.

convection (Sec. 137). In air-cooled engines (Fig. 491), the cylinder is provided with fins, over which the cooling air is circulated by a fan.

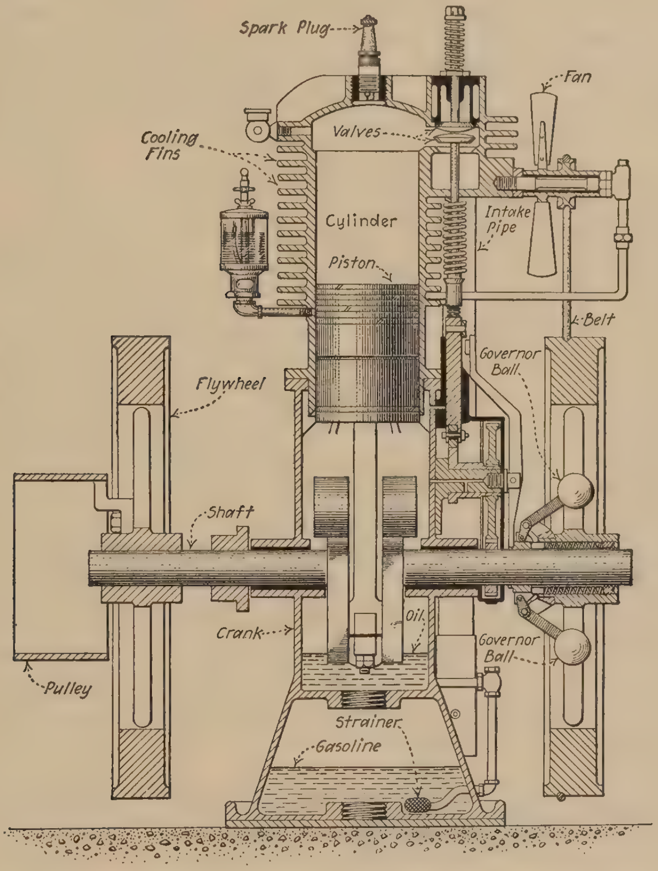


Fig. 491.—Air-cooled gasoline engine. (*New Way Motor Co.*, Lansing, Mich.)

553. The Cost Of Internal-combustion Engines given below is based on the average of values as given by Fernald and Orrok, "Engineering Of Power Plants," for stationary engines of 20-hp. capacity and above. The following costs are given in dollars per horsepower, f.o.b. factory: gas engines using city or natural gas, $37; producer-gas engines, $41; kerosene engines, $50; four-stroke-cycle Diesel engines, $56;

two-stroke-cycle Diesel engines \$35 to \$40. Foundations cost from \$2.50 to \$4 per horsepower. Erecting labor will cost from \$2 to \$3 per horsepower.

554. The Nameplate Horsepower Rating Of Internal-combustion Engines is, unless otherwise specified, usually as follows: (1) *For an Otto-cycle stationary engine*, nearly the maximum brake horsepower which the engine will develop at the shaft. Ordinarily, such engines are so rated that a load of from 5 to 15 per cent. above the rated horsepower at the rated speed will cause them to stall. Consequently, they have practically no overload capacity. (2) *For a variable-speed Otto-cycle engine*—automotive or marine—the maximum brake horsepower which the engine will develop at the shaft. (3) *For a Diesel-cycle engine*—Diesel or semi-Diesel—the brake horsepower at which the engine operates at its maximum efficiency. By increasing the period of fuel injection in a Diesel engine it can be made to develop more power than that for which it is rated, although such operation will be at a decreased efficiency. Some internal conbustion engines may, by their manufacturers, be given a horsepower rating which is higher or lower than the brake horsepower which the machine will actually deliver at its shaft. Consequently, the purchaser should insist on a guarantee from the manufacturer. In general then, internal combustion engines have little or no overload capacity above the outputs for which they are rated whereas steam engines (Sec. 508) usually have considerable overload capacity above their ratings.

Note.—The Brake Horsepower Which An Internal Combustion Engine Will Deliver At The Shaft may be very closely approximated by the following formula:

$$\text{(353)} \qquad \mathrm{P}_B = \left(\frac{d^2LN}{k_1} - k_2\right)k_3 \qquad \text{(b. hp.)}$$

Wherein: P_B = the brake horsepower which the engine delivers at the engine shaft. d = diameter, in inches, of the cylinder. L = piston stroke, in inches. N = revolutions per minute. k_3 = number of working cylinder ends. Thus, in a 2-cylinder double-acting engine, $k_3 = 2 \times 2 = 4$. k_1 and k_2 are constants which vary with the type of engine and the fuel used. Following are values of k_1 and k_2 for use in the above formula for engines of different types using various fuels. (1) *For an engine using producer gas*, $k_1 = 18{,}500$; $k_2 = 2$. (2) *For engines using natural gas*, $k_1 = 15{,}200$; $k_2 = 0.5$. (3) *For single-acting, vertical* *or horizontal engines using illuminating gas,* $k_1 = 15{,}700$; $k_2 = 2$. (4) *For double-acting horizontal engines using blast-furnace gas,* $k_1 = 21{,}000$; $k_2 = 0.5$. (5) *For single-acting horizontal or vertical engines using gasoline;* $k_1 = 16{,}400$; $k_2 = 0.5$. (6) *For single-acting horizontal or vertical engines using oil or distillate;* $k_1 = 21{,}875$, $k_2 = 0.75$. For. (353) and values of k_1 and k_2 which are given above are from ULBRICHT AND TORRANCE, "American Practice In The Rating Of Internal Combustion Engines." The above For. (353) is for stationary, four-stroke-cycle engines which operate on the Otto cycle. Therefore, it should not be applied to Diesel and semi-Diesel engines, nor to two-stroke-cycle engines.

QUESTIONS ON DIVISION 16

1. Explain the successive steps of converting the chemical energy of a fuel into mechanical work in an internal-combustion-engine power plant. In a steam power plant.
2. What is an internal-combustion engine?
3. Name the different kinds of fuels which may be utilized in an internal-combustion engine.
4. Explain how the air for combustion is generally mixed with a gaseous fuel.
5. Describe the operation of a producer-gas power plant.
6. How is air generally mixed with a light-liquid fuel. With a heavy-liquid fuel?
7. Name and explain three different methods which are employed for igniting the fuel in internal-combustion engines.
8. Explain three methods of internal-combustion-engine governing.
9. Explain with diagrams, the cycle of operations for a two-stroke-cycle engine. For a four-stroke-cycle engine. What are some of the advantages and disadvantages of each?
10. What is meant by "compression pressure?"
11. Explain the operation of a low-pressure internal-combustion engine using a light-liquid or a gaseous fuel. Of a low-pressure oil engine.
12. Explain the operation of a semi-Diesel engine. Of a Diesel engine.
13. Upon what two modified cycles do nearly all modern internal-combustion engines operate?
14. How may an internal-combustion engine be tested?
15. What are some of the causes for the difference between the thermal efficiency of a steam engine and that of an internal-combustion engine?
16. How may the thermal brake efficiency of an internal-combustion engine be obtained?
17. Why must the cylinders of an internal-combustion engine be cooled? Explain the different methods of cooling which are employed.
18. Upon what basis are internal-combustion engines of different types rated?

PROBLEMS ON DIVISION 16

1. A number of indicator cards were taken during the test of a four-stroke-cycle Diesel engine from each of the 4 cylinders. The average of the mean effective pressures as determined from the indicator cards was 106 lb per sq. in. The length of the stroke was 2 ft. and the diameter of the piston was 16 in. During the test the engine was running at 200 r.p.m. What was the total indicated horsepower of the engine during this test?
2. During a brake test of a producer-gas engine, it developed 140 b.hp. During the test, the rate of fuel consumption was 15,400 cu. ft. per hr. The heating value of the fuel was 128 B.t.u. per cu. ft. What was the thermal brake efficiency during the test?
3. What is the approximate brake horsepower which will be developed by a single-acting, single-cylinder gasoline engine which has a 7½-in. diameter cylinder and a 12-in. stroke when operating at 300 r.p.m.?

DIVISION 17

BUILDING WARMING

555. Artificial Warming Of Building Interiors Is Necessary in certain climates. In the torrid zones closed buildings are not, from the standpoint of bodily warmth, necessary. But in the temperate and arctic zones, buildings of some sort or other are essential to protect the inhabitants from the low temperatures. Provision must be made for warming the interiors of buildings.

556. Climatic Conditions Determine Largely The Refinement And Size Of The Heating System which is required for any given building. If the winter season is short and mild, a simple inexpensive plant which emits but a relatively small amount of heat will suffice for a certain building. But, where winters are severe, and where strong winds prevail during the cold season, not only must the building be more carefully constructed so that the heat loss from it will be a reasonable minimum, but also the interior-heating plant must be more elaborate.

Note.—Location And Character Of Occupancy Must Be Considered In Planning A Heating System.—If a building is on a high hill without protection from the wind, more heat must be expended to maintain its interior at a comfortable temperature than if it is protected from the wind. Other buildings in the immediate neighborhood and many adjacent trees may constitute such protection. Because of the prevailing winds in winter, more heat is required (in the Northern Hemisphere) for rooms on the north side of a building than for those on the south side. A building used for office purposes, wherein the occupants expend but little physical effort, must, for comfort, be kept at a higher temperature than must a structure which is used for manufacturing and in which the occupants continually exert themselves physically. The customary temperatures for buildings of different kinds are given in Table 557.

557. Table Showing Inside Temperatures Which Are Usually Assumed In Building-warming Calculations.—From Heating and Ventilation by Allen and Walker.

	Space	Temperature, deg. Fahr.
HEATED	Residences	70
	Lecture rooms and auditoriums	65
	Factories for light work	65
	Factories for heavy work	60
	Offices and schools	68 to 70
	Stores	65
	Prisons	65
	Bathrooms	72
	Gymnasiums	55 to 60
	Hot houses	78
	Steam baths	110
	Warm-air baths	120
UNHEATED	Cellars and closed rooms	32
	Vestibules frequently opened to the outside	32
	Attics under a roof with sheathing paper and metal or slate covering	25
	Attics under a roof with sheathing paper and tile covering	32
	Attics under a roof with composition covering	40

558. The Burning Of Fuels Constitutes The Most Important Source Of Building Warming.—Any of the available fuels (see Div. 13) may be employed for warming buildings. Which fuel is the most suitable for a given condition is usually determined by the locality and is largely a question of economics. A portion of the fuel which is used for heating, when it is burned, combines with oxygen as explained in Div. 14 and thereby liberates heat. The fuel may either be: (1) *Burned within the building* (Fig. 492) *which is to be warmed.*

(2) *Burned in a structure exterior* (Fig. 493) *to the warmed building.*

Note.—When Fuel Is Burned Within The Building, either a stove, fireplace, hot-air furnace, or steam or hot-water boiler (see following illustrations) may be employed. When the fuel is burned outside of the building, either hot-water, steam, or electric transmission of the heat to the building, is usually adopted

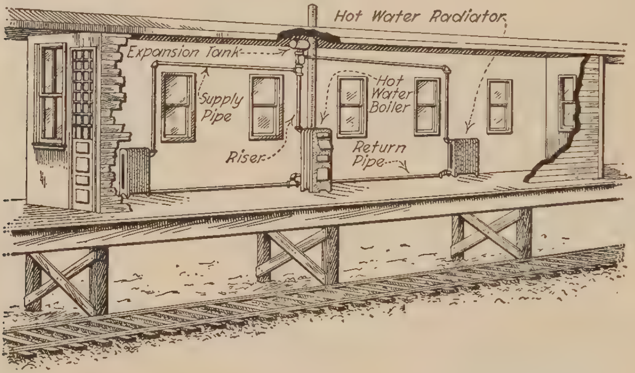


Fig. 492.—Building warmed by burning fuel within the building. (This shows a simple hot-water heating installation in a railroad station.)

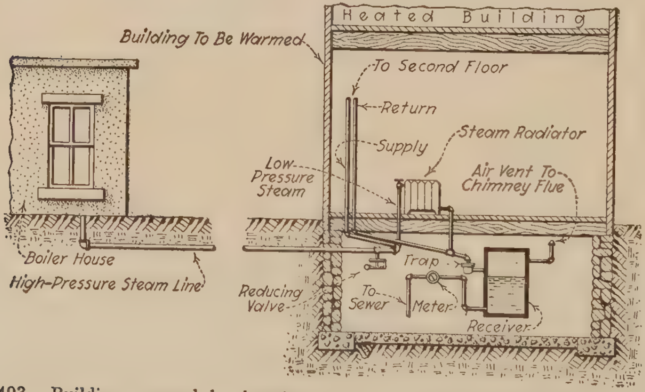


Fig. 493.—Building warmed by burning fuel in a building exterior to it. (Steam heating system.)

559. When Water Power Is Used For Building Heating (Fig. 494), waterwheels or turbines, which drive electric generators, convert the mechanical energy of the falling water into electrical energy. Then, the electrical energy is transmitted over wires to the building, and therein it is converted into heat energy; see Sec. 30.

Note.—There Are Other Sources Of Heat For Warming Buildings.—Thus in a building where machinery is in operation, the friction loss in the bearings (Sec. 576) and other electrical and mechanical losses are converted into heat energy. This heat, by radiation, conduction, and convection, raises the temperature of the room interior. Artificial-lighting devices burning in a room heat it: see Sec. 615 on electric heating. Human beings in a room at a temperature of 70° F. give off heat at the following rates: Adults at rest, 440 B.t.u. per hr. Adults at work, 450 to 600 B.t.u. per hr. Adults at violent exercise, 600 to 1,200 B.t.u. per hr. Children, 240 B.t.u. per hr. Infants, 65 B.t.u. per hr. A general figure of 400 B.t.u. per hr. per occupant is, however, frequently used in heating calculations.

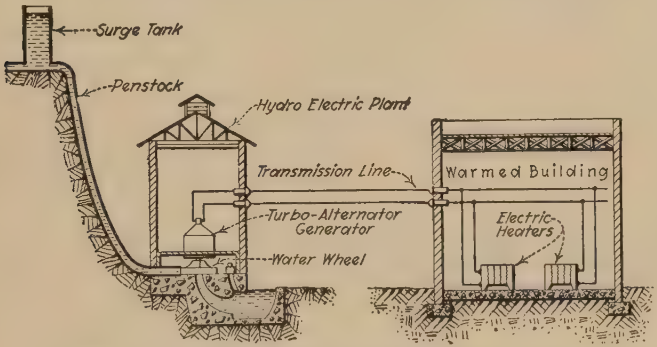


Fig. 494.—Building warmed by water power transmitted electrically.

560. The Heat For Warming A Room May Be Transferred Thereto, From The Device In Which The Heat Is Developed, By Radiation, Conduction, And Convection, all of which are discussed in Div. 5, Transfer Of Heat. Usually some of the heat is transferred by each of these three methods.

561. The Quantity Of Heat Which Must Be Supplied To A Room *during a certain time interval to maintain it at a constant temperature is equivalent to the amount of heat which escapes or is lost from the room during that time interval.* The heat loss from the room may occur through either radiation, conduction, or convection.

Example.—If the interior of a certain room (Fig. 495) is at a temperature of 70° F. and the heat loss from that room to the outside is 16,000 B.t.u. per hr., then, if heat is supplied to the interior of the room at the rate of 16,000 B.t.u. per hr., the room will thereby be maintained at a constant temperature of 70° F.

562. The Procedure In Designing A Heating Installation For Any Given Room Or Building is then, so it logically follows from the statement of Sec. 561, to: (1) *Determine, in the manner to be indicated, the heat loss per hour from the space to be warmed.* (2) *Select and proportion the heat-supplying equipment so that it will supply the same amount of heat per hour as that (determined above) which is lost.* The method will be illustrated in examples which follow.

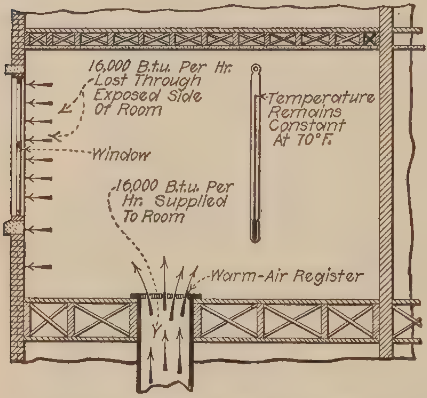

16,000 B.t.u. Per Hr. Lost Through Exposed Side Of Room
Temperature Remains Constant At 70°F.
Window
16,000 B.t.u. Per Hr. Supplied To Room
Warm-Air Register
Y

Fig. 495.—By supplying heat to a room at the same rate as that at which the heat is lost, the temperature within the room is maintained constant.

563. Heat Is Lost From A Building in one or more of three different ways: (1) *By conduction through walls, ceilings, floors, and windows.* (2) *By leakage or infiltration of air through cracks around doors and windows, through the walls, partitions, floors, and through the doors and window areas when these may be opened.* (3) *By ventilation.* Each of these modes of heat loss is discussed in following sections.

564. The Factors Which Determine The Quantity Of Heat Which Is Lost From A Building By Direct Conduction through walls, ceiling, floor, and windows, disregarding the effect of the exposure factor (Sec. 570) are: (1) *The temperature difference* (Sec. 565) *between the inside and outside of the room.* (2) *The materials, and method of construction of the room;* see Sec. 566. Each will be discussed.

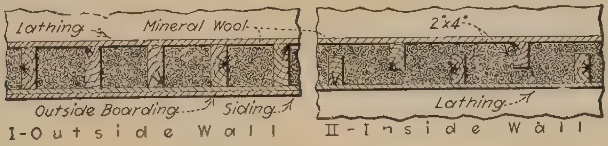
565. The Difference Between The Inside And Outside Temperatures Is Equivalent To The Thermal Pressure (see

Sec. 116) whereby the heat is caused to flow from the inside to the outside of the room. The solution of all building-heating problems must start with the assumption of definite values (see note below) for inside and outside air temperatures. In reality, the heat loss from any room of a building can be determined by applying the principles of heat transfer which are explained in Div 5. And actually it is these principles which are applied. But in practice, it has (as will be shown) been found much more convenient and quite as accurate to utilize certain empirical constants rather than to endeavor to follow rigidly the precise theoretical processes which are explained in Div. 5.

Note.—The Temperature Differences Ordinarily Assumed In Building-heating Computations have been fairly well standardized for different sections of the country. It is generally assumed that the inside air should be maintained at the values given in Table 557. In the southern zone of the United States, it is usually assumed, in designing, that the minimum outside temperature will be +10° F.; in the central zone, 0° F.; and in the northern zone and Canada, −10° F. If local conditions are such that the above-specified temperature differences will not satisfy, then others which do satisfy may be assumed.

Note —When A Partition (Floor, Wall, Or Ceiling) Separates Two Spaces, Both Of Which Are To Be Heated to the same temperature, no heat loss occurs through such a partition. Thus if two adjacent rooms, are artificially warmed, there is no heat loss through the partition wall. Since the temperature on both sides of the partition is the same, there is no thermal pressure (Sec. 116) through it. Hence, no heat transfer can occur

566. Different Materials Which Are Used In Building Construction Have Different Values Of Thermal Conductivity



I-Outside Wall II-Inside Wall

Fig. 496.—Mineral-wool wall and partition insulation.

(see Div. 5, Transfer Of Heat). Hence, the different materials will conduct the heat from the inside of a warm room to the outside cold air at different rates. Also as was explained in Div. 5, the thermal conductance of a given material varies inversely as the thickness of the material; the thicker the material the less its thermal conductance. Table 567 gives experimentally determined values of such conductances. These values are, as hereinafter explained, employed in For. (356) for determining the heat loss from a room or building.

Note.—Heat-insulating Materials Are Sometimes Interposed In Walls And Floors (Fig. 496) to minimize the heat loss. Or for the same reason, a wall may be constructed of hollow tile or hollow brick which provide dead air spaces.

567. Table Of Heat-transfer Coefficients Of Building Materials in British thermal units transmitted by conduction per square foot per hour per degree Fahrenheit temperature difference between inside and outside of building. (Hoffman, Heating And Ventilation.)

Materials and construction	K (For. 356)
8-in. brick wall	0.4
12-in. brick wall	0.31
16-in. brick wall	0.26
20-in. brick wall	0.23
24-in. brick wall	0.21
28-in. brick wall	0.19
32-in. brick wall	0.17
Brick wall, furred, use 0.7 times above values	
Stone wall, use 1.7 time brick-wall values.	
Windows, single glass	1.0
Windows, double glass	0.6
Skylight, single glass	1.1
Skylight, double glass	0.7
Wooden door, 1 in. thick	0.4
Wooden door, 2 in. thick	0.36
Solid plaster partition, 2 in. thick	0.6
Solid plaster partition, 3 in. thick	0.5
Ordinary stud partition, lath and plaster on one side	0.6
Ordinary stud partition, lath and plaster on both sides	0.34
Concrete floor on brick arch	0.2
Fireproof construction as flooring	0.1
Fireproof construction as ceiling	0.14
Single wood floor on brick arch	0.15
Double wood floor, plaster beneath	0.10
Wooden beams planked over, as flooring	0.17
Wooden beams planked over as ceiling	0.35
Walls of the average wooden dwelling	0.30
Lath and plaster ceiling, no floor above	0.62
Lath and plaster ceiling, floor above	0.25
Steel ceilings, with floor above	0.35
Single ¾-in. floor, no plaster beneath	0.45
Single ¾-in. floor, plaster beneath	0.26

568. The Factors Which Determine The Loss Of Heat From A Room Due To Infiltration Or Leakage Of Outside Cold Air are: (1) *Exposed wall area.* (2) *Area of openings of cracks through the wall, around doors and windows and the like.* (3) *Frequency with which the doors and windows are opened and closed and the length of time they remain open,* as for example when occupants pass in and out. It is infeasible to recognize individually and accurately all of these variable factors in the engineering computation of heat loss. Experience has, however, shown that certain coefficients (Table 569) may be applied, which will, under ordinary conditions correct with sufficient accuracy for this infiltration loss. These coefficients (*N*, Table 569) are based upon the ratio of cubical contents to exposed wall and door and window space, and upon the character of occupancy, and location of the room.

Example.—Referring to Table 569, it is assumed in building-warming computations, that the air in the hall of an ordinary residence undergoes, due to infiltration, three complete changes per hour.

569. Table Showing Number Of Complete Air Changes Usually Assumed Per Hour, Due To Infiltration.

Type of room	*N* Number of air-changes per hour
Residence:	
Halls	3
1st-story rooms	2
2nd-story rooms	1
Offices and stores:	
1st-story rooms	2.0 to 3
2nd-story rooms	1.5 to 2
Churches and public assembly rooms	0.75 to 2
Large rooms with small exposure	0.5 to 1

570. The Heat Loss From A Room By Conduction And Infiltration May Vary According To The Direction Of Exposure; see Table 571. The heat which is lost by conduction through the walls of a room is given off from the wall to the outside air by radiation, conduction, and convection. Now, if moving air is sweeping over the outside wall surface, heat which has been transmitted through the wall will be "wiped off" and carried away more rapidly than if the outside air which is in contact with the wall is still. Obviously then, a room which is located on the windward side of a building will have a greater heat loss than a similar room on the leeward side. Furthermore, the exposure direction affects infiltration. Thus, when a strong wind impinges on a certain side of a building, more air will be forced in through the cracks and crevices on that side than there would be if there were no wind. Since the prevailing cold winds in the Northern Hemisphere come from a northerly direction, it is evident that a room (Table 571) which has a northern exposure will experience a greater heat loss than a like room with a similar southern exposure.

NOTE.—THE METHOD USED FOR COMPUTING THE HEAT LOSS DUE TO EXPOSURE in building-warming computations is to employ certain coefficients (k_E, Table 571), the values of which have been determined by practice. It is infeasible to satisfactorily compute on a purely theoretical basis the effect of exposure.

NOTE.—INTERMITTENTLY HEATED ROOMS HAVE GREATER HEAT LOSS when heated than do rooms which are heated continually. To insure that such rooms may be heated in a reasonable time, a percentage is added to the computed heat losses. Intermittently heated rooms are given proper consideration by using the factors of Table 572.

571. Table Of Coefficients Of Exposure.

Direction of exposure	Coefficient k_E
North, north-east, and north-west	1.1 to 1.2
East or west	1.05 to 1.1
South	1.0

EXAMPLE.—From Table 571, the *exposure coefficient*, k_E, for east or west rooms is 1.05 to 1.1. This means that the heat loss, by conduction and infiltration, for an east- or west-exposed room, will be from 5 to 10 per cent. greater than or 1.05 to 1.1 times that for the same room if it had a southern exposure.

572. Table Of Coefficients For Intermittently Heated Rooms. (From Hoffman's HANDBOOK FOR HEATING AND VENTILATING ENGINEERS.)

Manner of heating	Coefficient k_I
Rooms heated only periodically	1.20 to 1.40
Heat interrupted daily but rooms kept closed	1.10
Heat interrupted daily but rooms kept open	1.25
Heat off for long periods	1.50

573. The Basis Of The Determination Of The Amount Of Heat Lost From A Room Because Of Its Ventilation is this: For each cubic foot of outside air which enters a room from any source whatsoever, 1 cu. ft. of the air that was in the room is forced outside, either by convection, or in some other way. If it were not thus forced out, the air would "pile up" in the room, which is impossible. When the temperature of the air within the room is higher than that of the outside air, then the air which is thus forced outside causes a loss of heat from the room. Hence, if the temperature within the room is to be maintained constant, the incoming air must be warmed to inside room temperature. The heating equipment should be so designed that it will effect this warming.

NOTE.—FROM TABLE 251 OF THE SPECIFIC HEATS, it will be noted that it requires 0.241 B.t.u. to raise the temperature of 1 lb. of air 1° F. Hence, it is evident, since there are approximately 13.3 cu. ft. in a pound of air at room-warming temperatures, and pressures, that it requires: 0.241 ÷ 13.3 = 0.018, or (approximately) 0.02 *B.t.u.* to raise the temperature of 1 cu. ft. of air, at room-warming temperatures, 1° F. In room-heating computations, it is therefore usually assumed that the loss of heat due to ventilation is 0.02 *B.t.u. per cu. ft. per degree Fahrenheit difference* between inside and outside temperatures. Conversely, 1 B.t.u. will raise the temperature of (1 ÷ 0.018 =) 55 cu. ft. of air through 1° F.

NOTE.—THE QUANTITY OF AIR REQUIRED FOR VENTILATION FOR RESIDENCE OR OTHER BUILDINGS WHEREIN THERE ARE BUT FEW PEOPLE is so small that special ventilating apparatus is, usually, unnecessary. There should, however, always be some ventilation in all rooms occupied by human beings. But, in the ordinary residence or similar room, sufficient fresh air enters automatically by infiltration (Sec. 568).

Therefore for buildings of these types such loss of heat as may occur due to ventilation is taken care of by the change-of-air factor which is discussed in preceding Sec. 568.

Note.—The Ventilation Required For Buildings In Which There May Be Many People such as schools, congested offices, churches, theaters, and the like, is based on the fact that to insure comfort, health, and mental activity, 1,800 cu. ft. of pure air per hr. is required for each person in the room. Hence, computations for rooms in which there are many people, may be made by the following formula; in which T = temperature difference, in degrees Fahrenheit between inside and outside air.

(354) *Heat loss per hr. by ventilation* = *No. persons* × 1,800 × 0.02 × T (B.t.u.)

Example.—Assuming that there are accommodations for 50 students in a certain school room, and that 1,800 cu. ft. of air per person per hr. will be supplied for ventilation, what will be the loss of heat per hour due to ventilation in this room? Assume 70° F. temperature difference. Solution.—Substituting in the above For. (354), *loss of heat due to ventilation* = *Number of persons* × 1,800 × 0.02 × T = 50 × 1,800 × 0.02 × 70 = 126,000 *B.t.u. per hr.*

Note.—For. (354) may also be written, assuming a 70° F. temperature difference:

(355) $$\mathbf{Q}_A = 2{,}520n \qquad \text{(B.t.u. per hr.)}$$

Wherein: $\mathbf{Q}_A$ = loss of heat, in British thermal units per hour, due to ventilation. n = number of persons.

574. The General Formula For Computing The Total Heat Loss From Any Room follows (see derivation below). For most practical computations, Carpenter's formula (Sec. 575) may be preferable. The following formula is included to illustrate the general principles involved:

(356) $$\mathbf{Q}_T = (A_G K_G T + A_W K_W T + A_F K_F T_F + A_C K_C T_C + 0.02\ NVT)k_E k_I + \mathbf{Q}_A$$

Wherein: $\mathbf{Q}_T$ = heat lost, in British thermal units per hour, that is, the heat, in British thermal units which must be supplied per hour. K_G, K_F, K_W, and K_C = coefficients of heat transfer for the glass, floor, walls, and ceiling, respectively in British thermal units per square foot per hour per degree Fahrenheit temperature difference, as found in Table 567. A_G = area of glass, in square feet. A_W = area of outside wall (exclusive of glass), in square feet. A_F = area of floor, in square feet. A_C = area of ceiling, in square feet. N =

assumed number of air changes per hour, as given in Table 569. V = volume of room, in cubic feet. T = temperature difference, in degrees Fahrenheit, between inside and outside of room (Sec. 565). T_F = temperature difference, in degrees Fahrenheit, between room and space under the floor. T_C = temperature difference, in degrees Fahrenheit, between room and space over ceiling. k_E = exposure coefficient, as found in Table 571. k_I = coefficient for intermittently heated rooms as given in Table 572. Q_A = heat, in British thermal units per hour, as computed by For. (354), which must be supplied to warm the air for ventilation.

DERIVATION.—By Sec. 563, all of the heat escapes from a room by conduction, infiltration, and ventilation. Or,

(357) $$Q_T = (Q_C + Q_F) + Q_A \quad \text{(B.t.u. per hr.)}$$

Wherein: Q_T = total heat loss from room, in British thermal units per hour. Q_C = heat loss, in British thermal units per hour, by conduction through glass, walls, floor, and ceiling. Q_F = heat loss, in British thermal units per hour, due to infiltration of outside air. Q_A = heat loss, in British thermal units per hour, due to ventilation from For. (354).

The rate of heat transfer by conduction through any substance of a given cross-sectional area and a given thickness is (Sec. 116) directly proportional to the temperature difference, or thermal pressure, causing the heat flow, and to the conductivity of the substance. Therefore, *the total heat loss, in British thermal units per hour through a building-partition = (Area of the partition in square feet) × (Thermal conductivity of the partition material) × (The temperature difference in degrees Fahrenheit).* But the total heat loss, Q_C, from a building by conduction is equal to the sum of the several losses which occur through the glass, walls, floor, and ceiling. Or,

(358) Q_C = (*glass loss*) + (*wall loss*) + (*floor loss*) + (*ceiling loss*) or, using equivalent symbols instead of words:

(359) $$Q_C = (A_G K_G T + A_W K_W T + A_F K_F T_F + A_C K_C T_C) \quad \text{(B.t.u. per hr.)}$$

Wherein all symbols are as specified under For. (356). The temperature difference between the warmed room and an unheated space adjacent to the ceiling or floor, such as a basement or attic, is, in practice, assumed to be 32° F.; see also Table 557.

From Sec. 568 and Table 569, a certain number of complete air changes per hour are assumed. Thus, if the assumed number of air changes per hour is multiplied by the cubical capacity of the room, the total number of cubic feet of air per hour which filters into the room will result. This air must be warmed from the temperature of the outside air to that of the inside air. From Sec. 573, it is found that 0.02 B.t.u. will raise the temperature of 1 cu. ft. of air 1° F. Therefore,

$$Q_F = 0.02NVT \qquad \text{(B.t.u. per hr.)} \tag{360}$$

Wherein all symbols have the same meaning as specified under For. (356).

But by Sec. 570, the heat loss due to conduction and infiltration is in some cases, augmented by the exposure or intermittent heating and the term $(Q_C + Q_F)$ must be multiplied by the coefficients, k_E, and k_I as found in Tables 571 and 572.

Now, if Fors. (359) and (360), with the coefficients, k_E, and k_I, applied to them, are substituted for their equivalents in For. (357), For. (356) results.

EXAMPLE.—The living room (Fig. 497), of a residence, which is located in the central zone of the United States, is 24 ft. long, by 16 ft. wide by 12 ft. high. The outside walls are of 12-in. furred brick. There are four outside windows, each having an area of 18 sq. ft. It is a two-story building wherein the basement is not heated. The second story is heated. Both the floor and ceiling are of wooden beams, planked over. What quantity of heat should be provided per hour for warming the room to 70° F. inside, when the outside air is 0° F.; see Sec. 565?

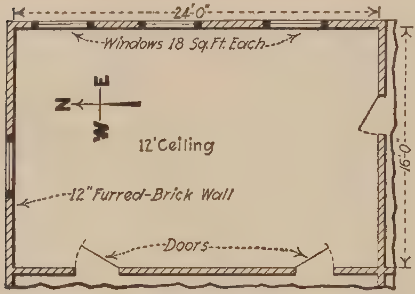


FIG. 497.—Computation of heat loss from a room. (First-story, residence living room; northeast exposure; 4 windows, 18 sq ft. each, second-story room heated; basement unheated; ceiling and floor are wooden beams, planked over.)

SOLUTION.—*Area of glass.* $A_G = (4 \times 18) = 72$ *sq. ft. Area of exposed wall, exclusive of glass* $= (24 \times 12) + (16 \times 12) - 72 = 408$ *sq. ft. Area of ceiling = area of floor* $= (16 \times 24) = 384$ *sq. ft. Cubical capacity of room,* $V = (16 \times 12 \times 24) = 4{,}608$ *cu. ft. Inside-outside temperature difference,* $T = 70 - 0 = 70°$ F. Temperature difference between the room to be warmed and the space adjacent to its ceiling is, since the second story is to be heated, 0° F.; and that between the room and the space adjacent to the floor is (see above) assumed to be 32° F. By Table 567, K, for glass = 1; for walls $= (0.7 \times 0.31) = 0.22$; for floor = 0.17; and for ceiling = 0 35 By Table 569, $N = 2$. By Table 571, $k_E = 1.1$. *The total heat loss,* For. (356), $= Q_T = (A_GK_GT + A_WK_WT + A_FK_FT_F + A_CK_CT_C + 0.02\ NVT)k_Ek_I + Q_A = [(72 \times 1)70 + (408 \times 0.22)70 + (384 \times 0.17)32 + (584 \times 0.35)0 + (0.02 \times 2 \times 4{,}608)70]\ 1.1 \times 1.0 + 0 = [5{,}040 + 6{,}273 + 2{,}088 + 0 + 12{,}900] \times 1.1 + 0 =$ 28,920 *B.t.u. per hr.* Or 28,920 *B.t.u must be supplied per-hour to* maintain a 70° F. temperature within the room with a 0° F. outside temperature.

575. Carpenter's Formula For Computing The Heat Loss From Any Room is stated below. This may be used in preference to the more complicated form of For. (356) for most building-warming computations. Prof. Carpenter states that the results as given by his formula and the corresponding results as "determined by actual experiment on a large scale for actual buildings" usually vary less than 5 per cent.

(361) $$Q_T = (A_G + 0.25\,A + 0.02\,NV)T \quad \text{(B.t.u. per hr.)}$$

Wherein: A = total exposed wall area including windows: also ceiling area and floor area if they are exposed to the outside air. All other symbols are as specified under For. (356).

DERIVATION.—For. (361) is merely a simplification of For. (356). For. (361) may be obtained from For. (356) by assuming: (1) K, *for glass* = 1. (2) K, *for all walls* = 0.25. (3) *That no heat loss occurs through ceiling and floors, except when exposed to outside air.* The exposure coefficient may or may not be considered, but a more consistent design will result from its use. If there is any heat loss due to ventilation, it should be added to the result as obtained from For. (361).

EXAMPLE.—What is the heat loss, in British thermal units per hour, from the room, example under Sec. 574, Fig. 497, as determined by Carpenter's formula? SOLUTION.—By For. (361), *The heat loss* = $Q_T = (A_G + 0.25A + 0.02NV)T = [72 + 0.25 \times (16 \times 12 + 24 \times 12) + 0.02 \times 2 \times 4{,}608] \times 70 = 26{,}320$ *B.t.u. per hr.* See note below.

NOTE.—IF THE EXPOSURE COEFFICIENT OF 1.1 IS APPLIED (as obtained from Table 571, for a north-east room) to the above solution, then, *the resulting heat loss* = $(1.1 \times 26{,}320) = 28{,}950$ *B.t.u. per hr.* The difference between the two results as given by For. (356) and by For. (361) is $28{,}950 - 28{,}920 = 30$ *B.t.u. per hr.* This is a negligible difference.

576. The Heat Which Is Supplied To A Room By The Persons, Lights, Or Machinery Therein, May, Properly, Be Deducted From The Total Heat, "Q_T" To Be Supplied Artificially as computed above. A room which is occupied by 100 adults would (Sec. 559) be supplied with: $100 \times 440 = 44{,}000$ *B.t.u. per hr.* by its occupants alone. *The rate of heat emission, in British thermal units per hour of an electric lamp when it is lighted = its wattage* × 3.415. Thus a 50-watt lamp emits: $50 \times 3.4 = 170$ *B.t.u. per hr.* Electric motors and the machinery which they drive, if both are located in the room, convert, in practically every case, all of the electrical energy, which is supplied to drive them, into heat. If the product of manufacture remains in the room until it has attained room temperature, all of this heat is, generally speaking, given up to warm the room. *The rate of heat supply, in British thermal units per hour, will in this case = (the motor horsepower ÷ motor efficiency)* × 2,545. Similarly, when mechanical power is supplied to a room for factory processes, usually, all of the energy thus transmitted to the room is ultimately converted into heat in the room, ordinarily by friction (Sec 86), which increases the room temperature.

Note.—In High-powered Mills this (Harding and Willard, Mechanical Equipment Of Buildings, Vol. I, p. 72) heat supplied by externally-generated power is the chief source of heating and is frequently sufficient to overheat the building even in zero weather, thus necessitating cooling by ventilation the year round.

Example—A 100-hp. squirrel-cage induction motor which has a full-load efficiency of 85 per cent. and which operates at full rated load is driving a line shaft in a furniture-factory room If the furniture which is manufactured remains in the room until it has attained room temperature, how many B t.u. are given up per hour to the room by the machinery during the manufacturing process? Solution.—By Sec. 576, *The rate of heat emission = (motor horsepower ÷ motor efficiency)* × 2,545 = (100 ÷ 0 85) × 2.545 = 300,000 *B.t.u. per hr.* (approximately).

577. Humidity Is Almost As Important As Ventilation In Rooms Occupied By Human Beings.—If the humidity (Sec. 331) is too low, the occupants of the room will experience

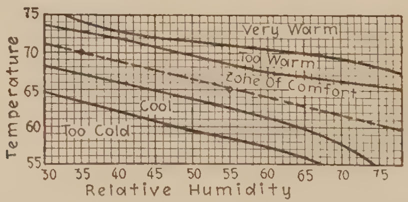


Fig. 498—Illustrating how one feels in still air at different temperatures and relative humidities As indicated by the two dots on the dashed line in the "Zone of Comfort," a person will feel as comfortable in a room at 65° F. and 55 per cent relative humidity as he will in a room at 70° F and 35 per cent relative humidity.

a "parched" sensation. The skin and the nasal passages will feel dry. Mental and physical depressions may result. Furthermore, low humidity is unhealthful because, after a person has remained in an atmosphere of relatively high temperature and low humidity and then goes out into the open air, he is likely to contract a cold or incur other disorders of the nose, throat, and lungs.

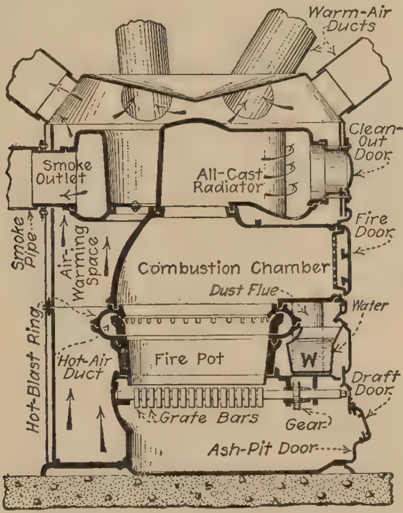
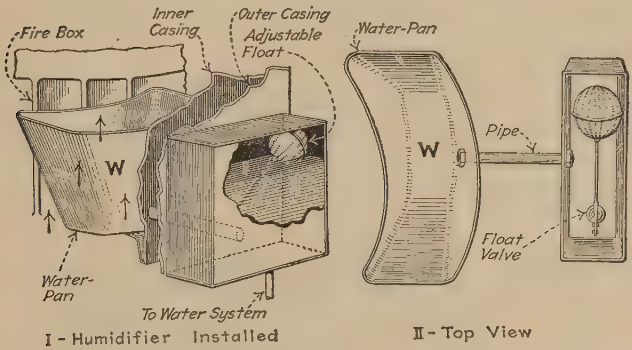


Fig. 499.—Water pan, *W*, in warm-air furnace. (*Fuller Warren Co.*)



I - Humidifier Installed II - Top View

Fig. 500.—Water-pan humidifier for warm-air furnace. (*Buck Stove & Range Co.*)

Note.—The Relative Humidity (Sec. 334) In Any Occupied Space Should Not Be Lower Than 45 To 55 Per Cent.—Furthermore, with the air in the room at a given temperature, a person will feel warmer where the relative humidity is high than where it is low. The temperature which he "feels" is the wet-bulb thermometer temperature (Sec.

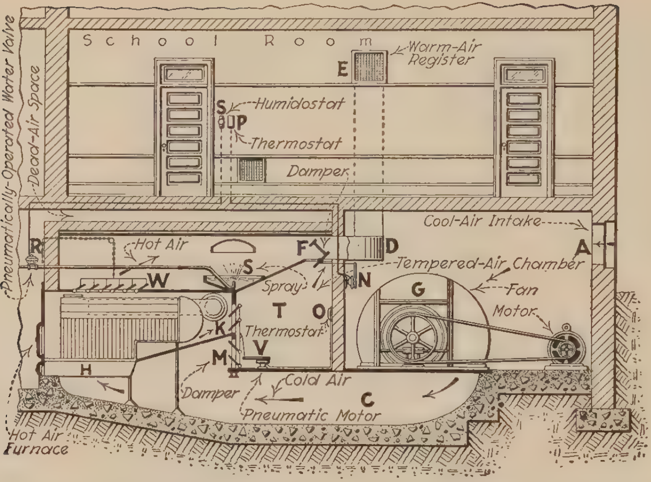


FIG. 501.—Humidifying apparatus in an indirect heating system. (KEENE, "Household Mechanics.") This shows only one of a number of the rooms which are heated. The air is drawn in at *A* to a motor-driven fan, *G*. The air, after leaving *G*, passes through a cold-air duct, *C*, to the heating surfaces, *H*, where it is warmed. The now-warmed air leaving *H*, enters the tempered-air chamber, *T*, through the passage, *K*. A damper, *M*, provides means for also admitting cold air to *T* directly from the fan. The thermostat, *O*, is connected with a pneumatic motor, *V*, which so regulates the supply of cold and warm air through *K* and *M* as to maintain the desired temperature for the air supply for the rooms above.

The air is humidified by a direct water spray, *S*. A part of the warm air from *H* may escape through the damper, *W*, and absorb water on its way to the duct, *D*—which takes the air to the room above—which room it enters through the register, *E*. The supply of the warm humid air is admitted to *D* in such quantity as will produce the desired degree of humidity in the rooms. The room temperature is governed by the thermostat, *P*, which, by means of the motor, *N*, controls the damper *F*. This damper admits warm humid air and the tempered air from *T* in proper proportion. When the humidity of the air in the room attains the maximum for which the humidostat is set, the humidostat, *S*, through its motor, closes the valve, *R*, which controls the water supply to the spray nozzle. Thereby the moisture in the air is decreased until a further amount is demanded.

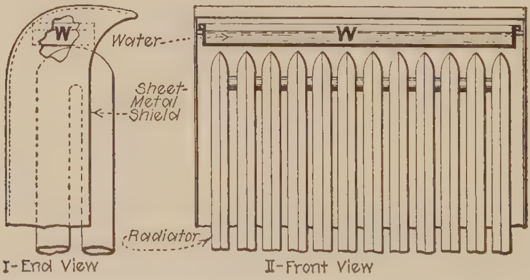


FIG. 502.—Water pan for humidifying the air on radiator of direct-heating system.

334), whereas the actual temperature of the room will be the dry-bulb thermometer temperature. The effect of humidity on the agreeable temperature is shown in Fig. 498. Hence, it actually requires less fuel to heat a space comfortably where the humidity within the space is high than it does if the humidity is low.

Note.—Proper Humidity May Be Provided Readily In Any Room.—If a warm-air furnace is used for heating a water-pan, *W*, (Figs. 499 and 500) may be arranged, in the air-warming passage of the furnace, adjacent to the fire box. The water becomes hot and evaporates into the up-going air and humidifies it. Sometimes the water boils and thus (Sec. 313) evaporates very rapidly. Where buildings are heated by the indirect method, suitably designed humidifying apparatus (Figs. 320 and 501) can be installed in the warm-air duct. In rooms heated by direct hot-water or steam-heating systems, water-pans (*W*, Fig. 502) may be placed on the tops of the radiators. The evaporation of their water humidifies the air. Where a stove is used for heating, water boiling in a kettle (Fig. 503) placed on its top will generally supply ample moisture.

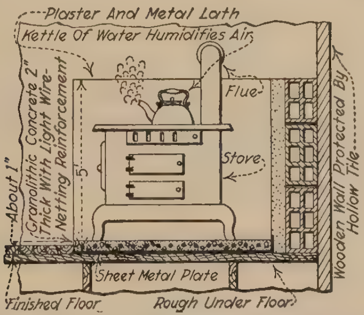

Plaster And Metal Lath
Kettle Of Water Humidifies Air
Flue
Stove
About 1"
Granolithic Concrete 2" Thick With Light Wire-Netting Reinforcement
5'
Wooden Wall Protected By Hollow Tile
Sheet Metal Plate
Finished Floor
Rough Under Floor

Fig. 503.—Steam from kettle of water humidifying room. (This also shows a method of fireproofing around a stove.)

578. The Principal Methods Of Warming Buildings may be classified as follows: (1) *Direct;* Fig. 506. (2) *Indirect;* Fig. 528. (3) *Direct-indirect;* Fig. 539, also called semi-indirect. Each of these methods is treated in succeeding sections. For definitions, see note below.

Note.—Direct Heating Is Effected By Warming The Air Of The Room Within The Room (Fig. 506) by some such means as fireplaces, stoves, or steam or hot-water radiators.

Indirect Heating Is Accomplished By Heating Air Outside Of The Room (Fig. 528) and then transmitting the warmed air to the room which is to be heated, through suitable ducts, either by convection or by forced draft.

Direct-indirect Heating (Fig. 539), as the name implies, is a combination of direct and indirect.

579. The More Common Types Of Apparatus Which Are Used For Building-warming are: (1) *Open-grate fireplace;*

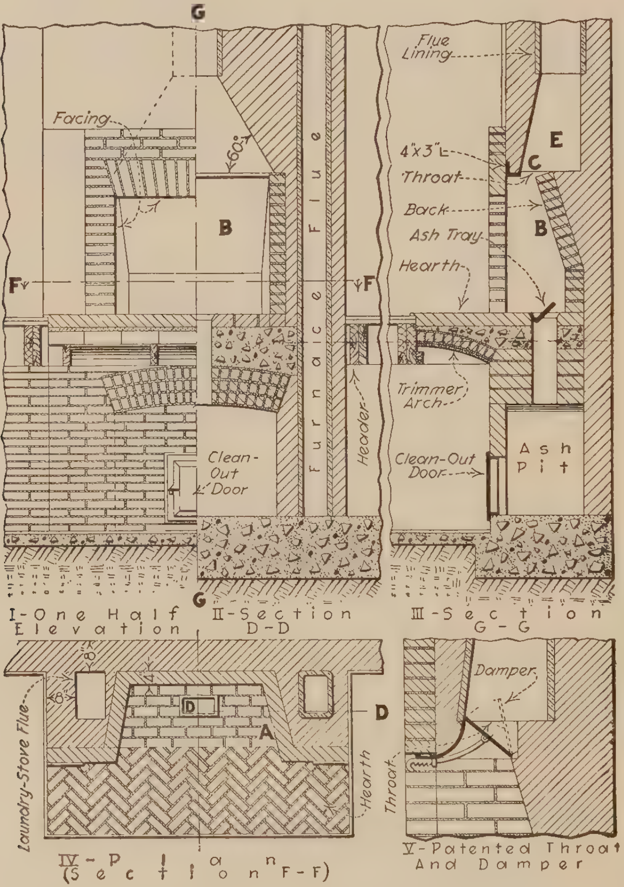


Fig. 504.—Typical open-fireplace construction. (*International Correspondence Schools'* Building Trades Handbook.)

Fig. 504. (2) *Stove;* Fig. 505. (3) *Hot-water radiators;* Fig. 506. (4) *Steam radiators;* Fig. 506. (5) *Warm-air furnaces;* Fig. 499. The scope of this book permits only a brief description of each. Other illustrations follow.

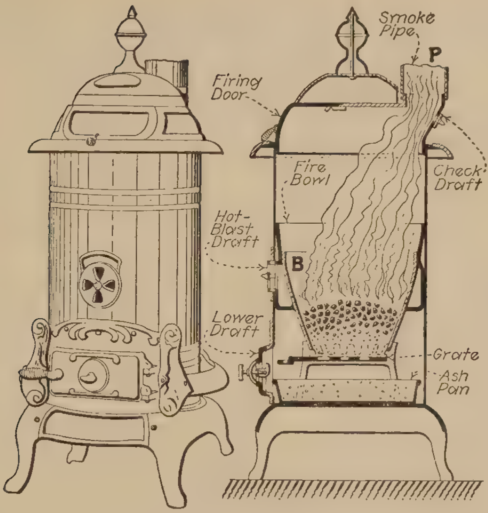


FIG. 505.—Heating stove.

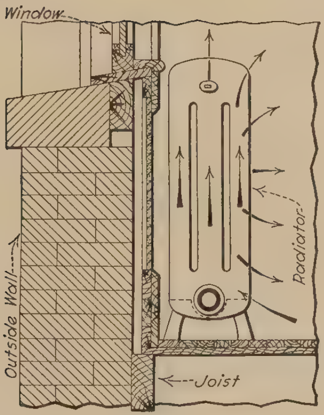


FIG. 506.—Diagram of direct heating radiator.

580. Table Showing Approximate Average Efficiencies Of Various Types Of Heating Installations.—These values are expressed as a percentage of heat given up to the heat-transfer medium—air, water or steam—as against the heat contained in the fuel.

Method of heating	Efficiency, per cent.
Cooking stove	1 about (in cooking) 70 to 80 (in heating)
Fireplace	5 to 20
Heating stove	70 to 80
Warm-air furnace	50 to 70
Steam heating	60 to 75
Hot-water heating	60 to 75

Example.—If 1 lb. of coal, which has a heat value of 11,000 B.t.u. (see Sec. 452) is burned in a fireplace, the amount of heat from this 1 lb. of coal which would be given off in heating the room might only be: 11,000 × 0.05 = 550 *B.t.u.* The remainder, or: 11,000 − 500 = 10,450 *B.t.u.* would be lost up the chimney.

Example.—A certain steam-heating furnace, which is located within the building, burns 10 lb. of coal per hr. If the thermal value of this coal is 14,000 B.t.u. per lb., what part of the heat in the coal is, probably, useful in heating the building? Solution.—From Table 580, the probable efficiency of a steam heating installation is about 67.5 per cent. Therefore *the heat effective in warming the building* = 10 × 14,000 × 0.675 = 94,500 *B.t.u. per hr.*, more or less. The remainder of the heat in the coal, or 45,500 *B.t.u. per hr.* is lost up the chimney.

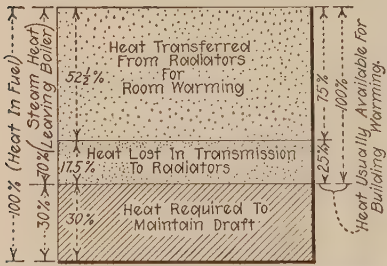

100% (Heat In Fuel)
70% (Steam Heat Leaving Boiler)
30%
52½%
Heat Transferred From Radiators For Room Warming
17.5%
Heat Lost In Transmission To Radiators
30%
Heat Required To Maintain Draft
75%
25%
100%
Heat Usually Available For Building Warming.

Fig. 507.—Graphical statement of steam-heating-plant efficiency. (Values for hot-water heating are substantially the same.)

Note.—A Graphical Statement Of Steam- And Hot-water Heating-plant Efficiency is presented in Fig. 507. About 30 per cent. of the total heat in the fuel is spent in maintaining the draft. In one sense, this 30 per cent. is not wasted inasmuch as combustion (Sec. 464) cannot be effected without draft. If heat from the fuel was not employed or producing draft, the draft would have to be produced by the expenditure of external power. But this 30 per cent. *is* largely wasted insofar as building warming is concerned. This leaves about 70 per cent. of the total heat in the fuel available for heat transmission and distribution.

If the entire heating plant is in one building, the 17.5 per cent. allowed (Fig. 507) for distribution is really not lost but is expended in warming cellars and other spaces through which the supply and return mains pass. Hence, in such a plant, about 70 per cent. of the total heat in the fuel is available for building warming. But if the heating-steam or water must be transmitted through relatively long pipe lines, then the 17.5 per cent.—or more—may be wholly lost in transmission.

581. The Applications, Advantages, And Disadvantages Of The Various Methods Of Building Warming are: FIREPLACES are: (1) *Very inefficient.* (2) *Dirty.* (3) *Do not produce even temperatures.* STOVES are: (1) *Relatively efficient.* (2) *Dirty.* (3) *May occupy valuable floor space.* HOT-WATER AND STEAM SYSTEMS have the following inherent characteristics: (1) *High first cost.* (2) *Positive heat transfer, therefore not affected by wind.* (3) *Applicable to both large and small installations.* (4) *Relatively inflexible in overload capacity.* GRAVITY-INDIRECT WARM-AIR SYSTEMS may be said to: (1) *Have large overload capacity.* (2) *Be relatively low in first cost.* (3) *May provide proper ventilation.* (4) *In some instances, be affected by wind.* THE HOT-BLAST WARM-AIR SYSTEM provides *positive ventilation at all times.*

582. The Open-grate Fireplace (Fig. 504) is the oldest type of heating apparatus now commonly used for warming buildings. From it the heat is transmitted to the room almost wholly by radiation. It provides a very inefficient heating method (See Table 580 and example subjoined thereto). About 80 to 95 per cent. of the heat of the fuel escapes through the flue and is ineffective in warming the room. An open-grate fireplace does, however, provide an excellent means of ventilation, since all of the air which is taken from the room and carried up the chimney by convection must be replaced by fresh air through infiltration from the outside. However, an open fireplace provides a pleasant and cheerful heating effect. Such fuels as coal, wood, coke, gas, and peat, may be burned in the fireplace.

NOTE.—TO BE MOST EFFECTIVE, A FIREPLACE MUST BE PROPERLY DESIGNED.—It should have sloping firebrick sides, and back, *A* and *B*, (Fig. 504) to reflect the heat into the room. The throat, *C*, should not be greater than 2.5 to 4 in. in depth and should be of the width of the fireplace opening. The total throat area should be at least equal to the total flue area. The smoke shelf, *E*, prevents air from rushing down when the fire is being started, and forcing smoke into the room.

583. The Stove is in general use, both for building-warming (Fig. 505) and for cooking (Fig. 508). In spite of its disadvantages the stove appears to provide the most economical method of heating where only a small amount of locally-generated heat is necessary. Stoves are usually made of cast iron or sheet iron. Each contains a fire bowl or box (*B*, Fig. 505) wherein the combustion (see Div. 14) of the fuel takes place. A smoke-pipe, *P*, connects the fire box to the chimney. Natural draft is employed in practically every case. Stoves may be obtained wherein practically any known fuel may be burned. Heat is transmitted from a heating stove by direct radiation, conduction, and convection. The warming efficiency of the average heating stove is (Table 580) 70 to 80 per cent., whereas, with the cooking stove, only about 1 per cent. of the heat of the fuel is actually utilized for cooking.

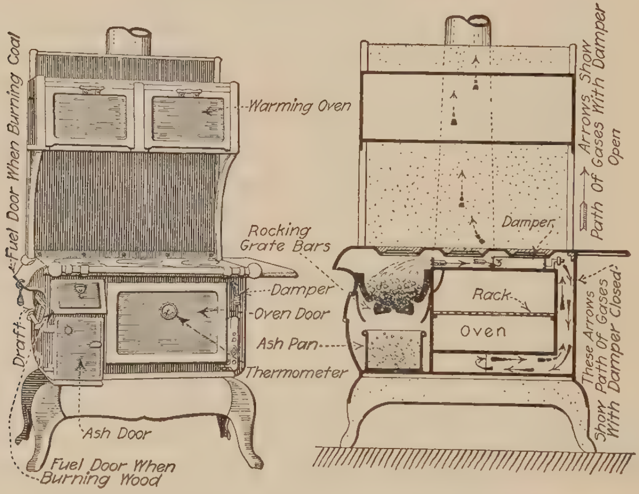

Fuel Door When Burning Coal
Warming Oven
Rocking Grate Bars
Damper
Oven Door
Ash Pan
Thermometer
Draft
Ash Door
Fuel Door When Burning Wood
Arrows Show Path Of Gases With Damper Open
Damper
Rack
Oven
These Arrows Show Path Of Gases With Damper Closed

Fig. 508.—Typical modern cooking range. (In the trade a "Stove" has two oven doors, one at each side of its oven. A "Range" has only one door to its oven.)

Note.—The Woodwork Located Near To Stoves Which Are Operated In Wooden Buildings Should Be Fireproofed.—An effective and comparatively inexpensive method of fireproofing a stove is shown in Fig. 503.

584. In Comparing Hot-water Or Steam Heating Systems With Warm-air Furnace Systems: the hot-water and steam plants have the advantages that their operation is not affected by wind pressures, and that, with them, heat may be readily transferred to any part of a building or community. They have the disadvantage, as compared with warm air, of about two to three times the cost for an equivalent installation. The hot-water and steam systems are, in general, (Table 580) somewhat more efficient. Hot-water and warm-air systems are more flexible than are steam systems in that a moderate rate of heating can be produced with them whereas the steam systems generally either heat at their maximum rate or not at all. The hot-water system is about 20 per cent. greater in first cost than is the steam.

585. Hot-water Heating Systems Are Of Two Classes: (1) *The gravity-return system*, which operates by convection (Sec. 586) only. (2) *The forced-circulation system*, wherein the circulation of the heated water is effected by a pump. The gravity system is effective in, and is usually employed, only in relatively small installations; see following sections. The forced-circulation system is used in hot-water district heating and for large industrial-plant buildings.

586. The Principle Of Gravity Hot-water Heating is discussed in Div. 5, Transfer Of Heat. The water is heated in the boiler (Fig. 509) which is located at the lowest point of the system, usually in the basement. The heated water then conveys the heat to the radiators by convection (Sec. 137) and there transfers a portion of its heat to the air of the rooms. The water is cooled thereby. Then it, now being heavier than the corresponding column of hot water in the supply pipe, falls by gravity to the boiler. Therein it is re-heated and the process continues so long as heat is supplied by the burning of the fuel in the boiler.

Note.—In A Gravity Hot-water Heating System All Of The Piping Should Be Entirely Full Of Water.—If it is not full, circulation cannot occur and it will cease to function as a heating system.

Note.—To Compute The Pressure Which Causes The Circulation Of The Water In A Gravity Hot-water Heating System the same general method is followed as that described in Sec. 256 for the computation of the pressure which produces a draft in a chimney. See following example.

Example.—What pressure head will be produced in a hot-water heating system wherein the average difference in elevation between the boiler and the radiators is 20 ft., if the average temperature of the water in the supply pipe is 180° F., and that in the return pipe is 160° F.

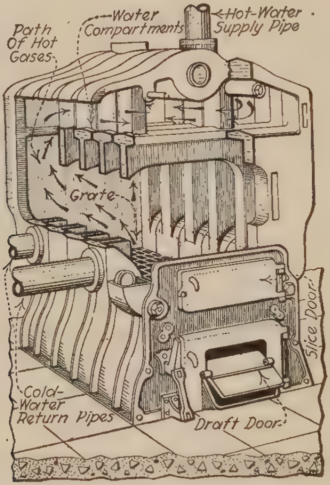


Fig. 509.—Typical medium-size, hot-water heating boiler. (*American Radiator Co.*) In general, the same boilers may be used for both steam and hot-water heating but steam space must be allowed above the water in a steam boiler.

Solution.—The weight of 1 cu. ft. of water at 180° F. is 60.554,7 lb., and at 160° F. 1 cu. ft. of water weighs 60.975,4 lb. *The difference in weight of* 1 *cu. ft. of water at* 180° *F. and* 160° *F.* $= 60.975{,}4 - 60.554{,}7 = 0.420{,}7$ *lb.* A column of water 1 sq. in. in cross section and 20 ft. in height contains: $20 \div 144 = 0.138{,}8$ *cu. ft. The difference in weight of this water column at* 160° *F. and at* 180° *F.* $= 0.420{,}7 \times 0.138{,}8 = 0.058$ *lb.* Therefore, *the pressure head produced in the system is* 0.058 *lb. per sq. in.*

Note.—The Circulating Pressure Obtainable In A Gravity Hot-water System Is Relatively Small, as is indicated by the preceding example. Hence, in such a system, the piping must be designed and erected very carefully so that it will offer minimum frictional opposition to the water-flow. In large buildings, or where a number of isolated buildings are to be heated by hot water, it is necessary to employ a pump to circulate the water, that is, a forced-circulation system must be used (see Fig. 527).

587. Several Methods Of Piping Are Employed In Hot-water Heating. The three principal piping systems are: (1) *The multi-branch or two-pipe system* (Figs. 510 and 511), which is the one ordinarily used for relatively small buildings such as residences. (2) *The circuit or one-pipe system* (Figs. 512 and 513), which requires no separate return main; this feature renders it especially adaptable to those apartment houses wherein each apartment has its own boiler, as it eliminates about half of the basement piping. However, it requires larger radiators than the multi-branch system. (3) *The overhead or "Mills" system* (Figs. 514 and 515), wherein the distributing main is located on the top floor, or in the attic. In each of these the general principle is the same. The arrows in the illustrations indicate the directions of water flow.

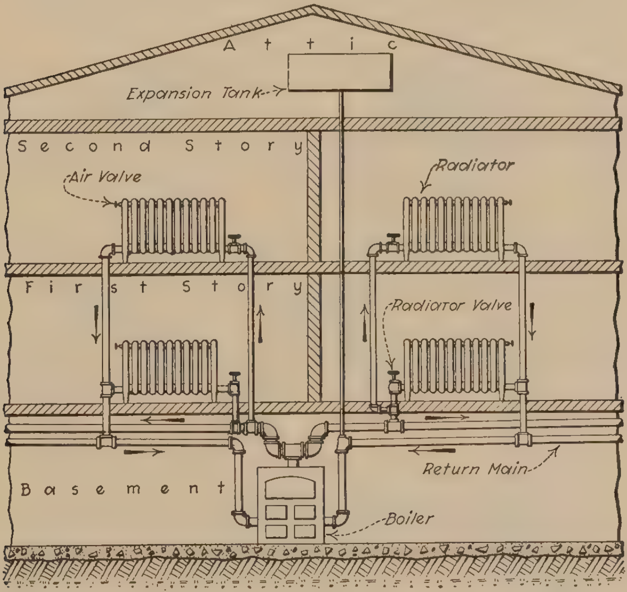


Fig. 510.—Multi-branch or two-pipe system of hot-water piping.

588. An Expansion Tank Is Required In Hot-water Heating Systems.—To insure circulation through the radiators of a hot-water heating system, all of the piping must be entirely full of water. Hence some means must be employed to insure this, and at the same time, prevent damage by the rupturing of some component of the system due to the expansion of the water (which will obviously occur when the water is heated). This is accomplished (Figs. 510, 512 and 514) by using an expansion tank. When the water in the system is heated, it expands into the expansion tank, *T*, (Fig. 516), which is normally about half full of water. The tank may be vented at *V* to the open air, thus permitting free expansion of the water in the system.

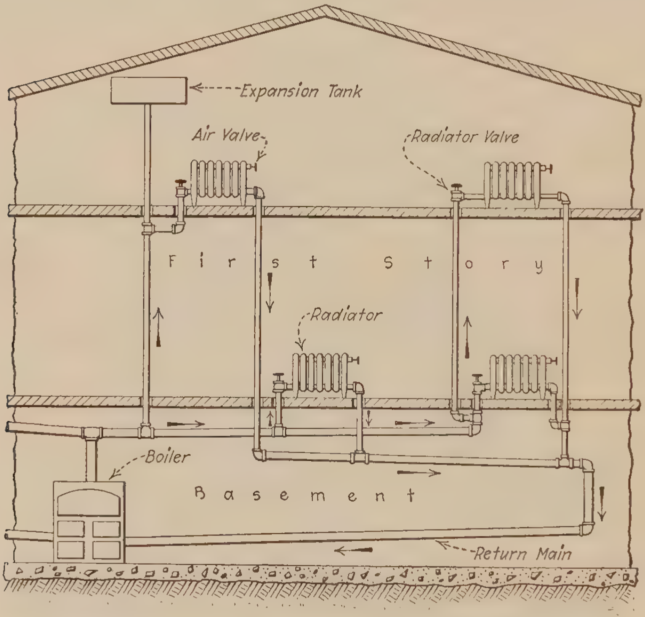


Fig. 511.—Reversed-return two-pipe hot-water system. This piping arrangement requires a little more pipe than does that of Fig. 510 but it provides circuits of practically the same length through all radiators. It thus tends to equalize the resistance to flow through all of the radiators.

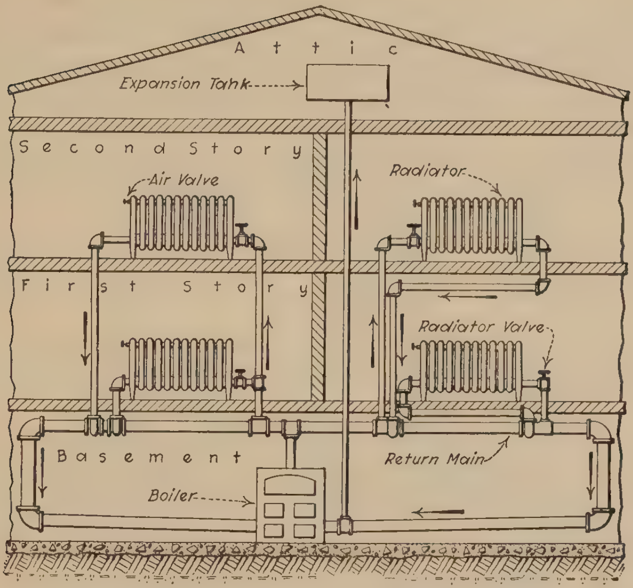


FIG. 512.—The one-pipe system of piping for hot-water heating. The radiators on the left are properly connected. Those on the right are connected poorly. Note the difference.

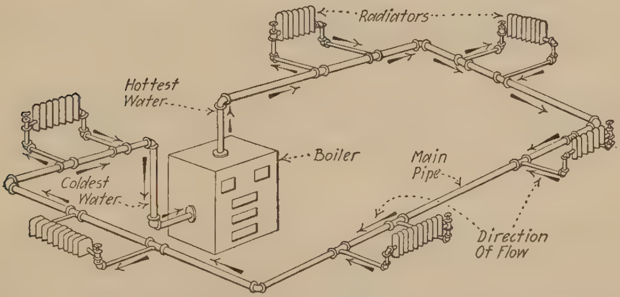


FIG. 513.—Illustrating the one-pipe circuit system of piping hot-water radiators. Each radiator receives colder water than the preceding one. Thus, the effectiveness of the later radiators is less than that of the earlier. The later radiators should, therefore, be made relatively large.

589. There Are Two Methods Of Expansion-tank Operation: (1) *The open-tank method,* wherein the system is open (*V*, Fig. 516) directly to the atmosphere. (2) *The closed-tank method,* wherein the system is not open to the atmosphere, but instead has interposed in it a safety valve, or equivalent device, which insures that the pressure on the system will be greater than atmospheric pressure but which prevents an excessive increase in pressure in the system.

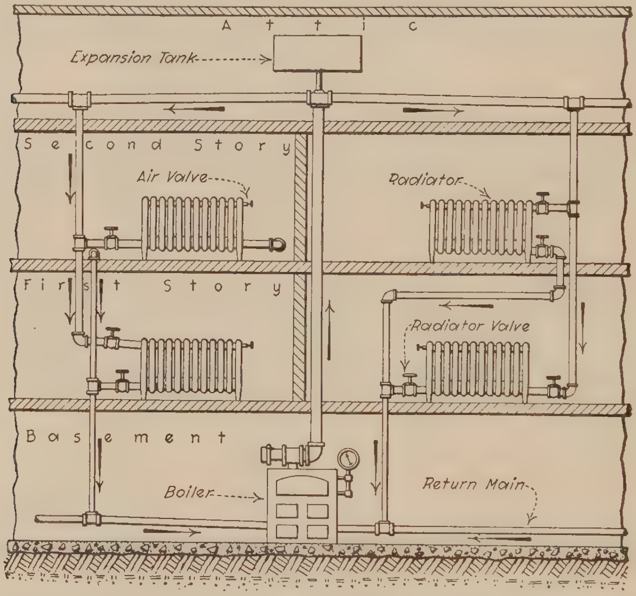


Fig. 514.—Two-pipe overhead or Mills system of piping for hot-water heating. Different methods of connecting the different radiators with risers are shown here. It is preferable to have the hot water enter each radiator at the top as in the lower left- and upper right-hand radiators The branches below the floor and behind the radiator are for taking up pipe expansion.

Explanation.—When The System Is Open To The Atmosphere, The Temperature Of The Water In It Cannot Exceed 212° F.—If it does tend to exceed 212° F. (which, Table 394, is the boiling temperature of water at atmospheric pressure) the hot water from the furnace as it reaches the tank, will vaporize into and discharge from the tank as steam. This limits the water temperature in the open-tank system to 212° F. The static head impressed on the water in the boiler, due to the weight of the column of water above it, may be such that the pressure on the water in the boiler is considerably greater than atmospheric pressure. The temperature of such water before it rises into an open expansion tank may be materially above 212° F. But if it is above 212° F. it will vaporize into steam bubbles in passing to the tank and discharge as such.

Now, if a safety valve, which is set to operate at a pressure of say 10 lb. per sq. in. above atmospheric pressure, is placed on the expansion tank, a closed-tank system will result. Then, the corresponding boiling temperature of the water under the increased pressure (see Steam Table 394) will be 240° F.

Thus, by arranging a safety valve on an expansion tank, the temperature, and the effectiveness, of the water in the heating system may be correspondingly increased. But experience has shown that ordinary safety valves installed on expansion tanks are subject to "sticking."

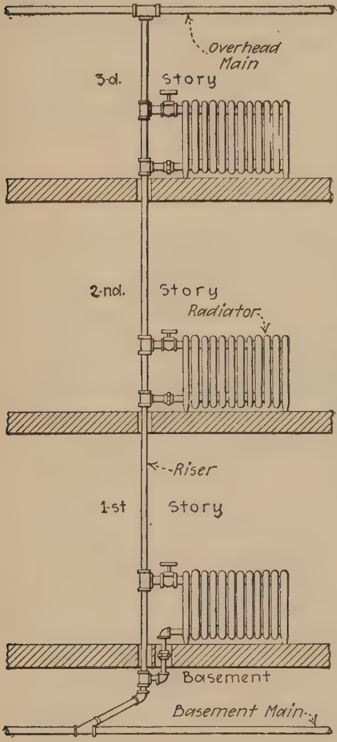


FIG. 515.

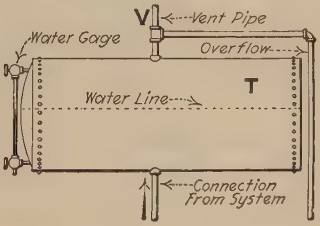


FIG. 516.

FIG. 515.—One-pipe overhead hot-water system. With this piping arrangement there is less "head" or pressure-difference on each radiator than with that of Fig. 514. Also the lower radiators here receive colder water than the upper ones—hence the lower ones must be larger.

FIG. 516.—Open type expansion tank for hot-water heating system.

They are, therefore, dangerous. Hence, in modern systems it is the practice to install in the riser to the expansion tank some device (for example, the *Honeywell Heat Generator*) which is the equivalent of a safety valve. It maintains automatically, on the hot-water circulating system, a pressure of say, 10 lb. per sq. in. above atmospheric—that is, 10 lb. per sq. in. gage; (see Sec. 16). But, if the pressure in the system exceeds 10 lb. per sq. in. gage, the device will relieve the excess pressure. Devices of this character should always be so simple that there is practically no possibility of their ever becoming inoperative.

590. The Rate Of Heat Radiation From The Radiators Of A Steam Or Hot-water Heating System is determined by their size and shape and by the average temperature of the water which circulates through them. Tests show that an average hot-water or steam radiator will give off about 1.7 B.t.u. per hr. per sq. ft. of radiating surface per degree Fahrenheit difference between the temperature of the water in the radiator and the temperature of the room. See Table 600 and Fig. 517.

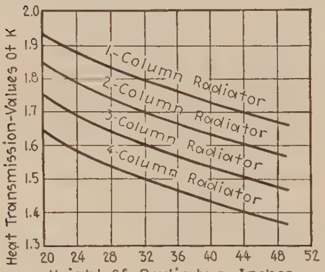


Fig. 517.—Graphs showing variations of the coefficient of heat transmission from radiators with radiator height.

Note.—The Normal Entrance And Exit Temperature Differences Of Hot-water Radiators are approximately: (1) *For the open system;* entrance temperature, 180° F.; exit temperature, 160° F. (2) *For the closed (Honeywell) system:* entrance temperature, 220° F.; exit temperature, 200° F. In both cases, the temperature drop in the radiator is about 20° F. Hence, the average radiator temperature for the open system is about 170° F., and for the closed system, about 210° F. Thus, assuming a room temperature of 70° F., *the difference between the average radiator temperature and the room temperature is, for the open system:* 170 − 70 = 100° F. *For the closed system, it is:* 210 − 70 = 140° F. Therefore, for the open system, it is ordinarily assumed in hot-water-heating computations that *the rate of radiator heat emission is:* 1.7 × 100 = 170 *B.t.u. per hr. per sq. ft. of radiating surface. For the closed system, the rate of heat emission will be:* 1.7 × 140 = 238 *B.t.u. per hr. per sq. ft. of radiating surface.* These values will vary somewhat with radiators of different types. See Table 600.

591. The Procedure In Proportioning The Radiating Surface Of A Hot-water Heating System For A Given Room Or Building is essentially the same as that used for designing a steam-heating system. It is described in following Sec. 599. For either hot-water or steam, the amount of radiating surface is selected such that the heat which is given off by the radiators is just sufficient to compensate for the heat loss (Sec. 561) from the room or building.

592. In Steam Heating Systems, steam (see Div. 11) is the medium whereby the heat is transferred from the location where it is generated, usually by the combustion of a fuel in a boiler (Fig. 518), to the room or building which is to be warmed. Since the steam in the radiators is at a higher temperature than the air in the space to be warmed, heat is transferred by conduction, radiation, and convection, from the radiator to the air in the space. Due to this loss of its heat, the steam in the radiator is caused to condense. It thus gives up its latent heat of vaporization (Sec. 329) to the room. Since, in general, steam-heated radiators operate at higher temperatures than do hot-water radiators, a lesser amount of radiator surface is, for equivalent conditions, sufficient in steam-heating systems.

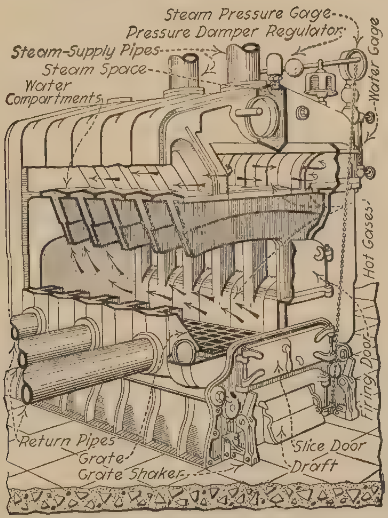


Fig. 518.—Typical medium-size, cast-iron, sectional steam-heating boiler. (The steam boilers used for large steam heating plants are essentially of the same construction as those used for power service, except that they may be designed for smaller pressures.)

593. A Comparison Of The Steam As Against The Hot-water Heating System may be stated thus: In general, a steam system is not as economical or as well adapted for moderate climatic conditions as is a hot-water system. On cool—not cold—days, a small fire will circulate the water in a hot-water system satisfactorily, but in a steam system, the fire under the boiler must always, if any heat whatsoever is to be given off by the radiators, be sufficient to maintain all of the water in the boiler at least at the boiling temperature. Therefore, while the first cost of a hot-water warming system may be greater than that of an equivalent steam system, the hot-water outfit will, for moderate conditions, probably be more economical and satisfactory in the long run. The hot-water system, however, has the disadvantage of not being adapted to changing the rate of heating as quickly as does a steam system. The great bulk of water in a hot-water system takes a greater length of time to warm.

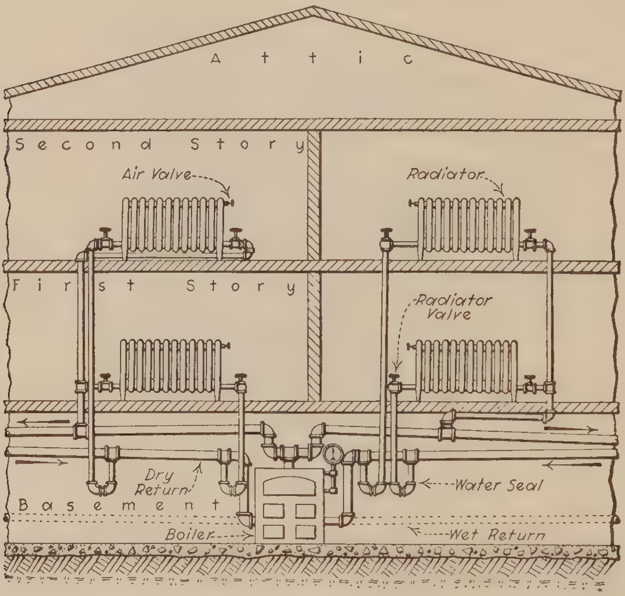


Fig. 519.—Two-pipe (basement-main) system for steam heating. Note the sealed returns. Without these seals, the steam might short-circuit through the radiators nearest to the boiler and not reach the others.

594. Direct Steam-heating Systems May Be Classified with respect to: (1) *The method of returning the water of condensation from the radiators to the boiler.* (2) *The method of piping.* (3) *Steam pressure.* Each of these will be discussed.

595. The Condensation Water In A Steam Heating System May Be Returned To The Boiler By Either Of Two Systems: (1) *The gravity-return system.* (2) *The forced-return system.* The gravity-return system (Figs. 519, 520 and 521) comprises a closed circuit, wherein the condensation water flows to the boiler by gravity. The forced-return system (Fig. 522 which is explained later) is not a closed system. With it, the pressure in the supply piping and radiators may be considerably higher than that in the return piping. That is, the condensate is returned to the boiler by means of a pump, return traps, or both.

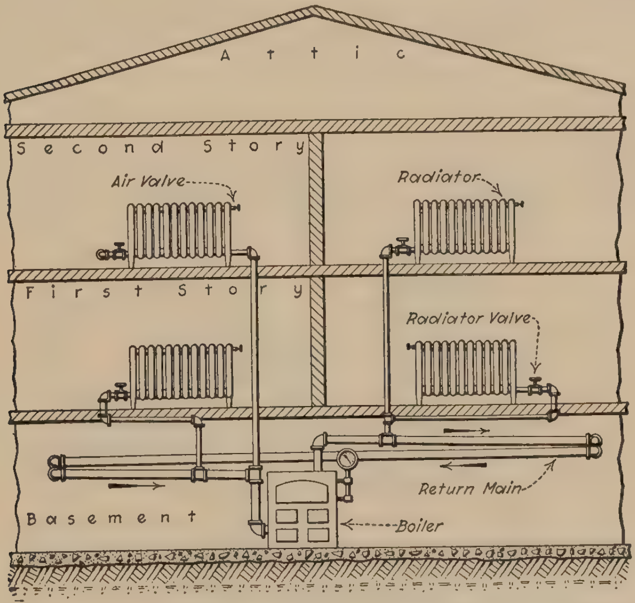


Fig. 520.—One-pipe (basement-main) for steam heating. Here again, as in Fig. 514, various radiator-connection arrangements are shown. The upper right-hand radiator may give trouble due to pipe expansion.

596. The Principal Methods Of Piping Used For Steam-warmed Buildings are: (1) *The two-pipe system;* Fig. 519. (2) *The one-pipe basement-main system;* Fig. 520. (3) *The one-pipe attic-main or "Mills" system;* Fig. 521. Various other arrangements, which are usually modifications of one of these three systems, are employed. For all systems, the general principle is the same.

Note.—A Comparison Of The Three Systems Of Piping which are illustrated in Figs. 519, 520 and 521, shows, for small buildings, but little difference in the cost of the one-pipe as against the two-pipe system. For large buildings, however, the one-pipe system is usually more economical. The two-pipe system is less susceptible to "water-hammer" noise. It is sometimes more economical in operation, especially when the radiators are equipped with steam traps (Fig. 522, explained later).

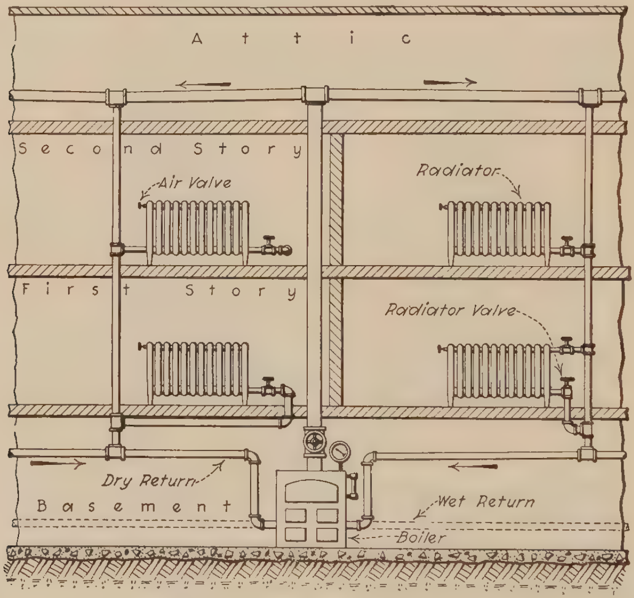


Fig. 521.—One-pipe (attic-main) or Mills system for steam heating. Each radiator is shown with a different kind of connection.

Note.—"Wet" And "Dry" Returns (Fig. 519) are so called, respectively, when the return pipe is below or above the water line of the boiler. The wet return insures against short-circuiting through the radiators but requires a little more pipe than does the dry return.

597. A Pressure Classification Of Steam-heating Systems is: (1) *High-pressure systems are those in which the steam pressure in the radiators is* 10 *lb. per sq. in. gage and above.* High-pressure systems are seldom used in building warming. (2) *Low-pressure systems are those in which the steam pressure* *in the radiators is something between atmospheric pressure and 10 lb. sq. in. gage.* Practically all building-warming installations for which steam is used as the heat-transmission medium are low-pressure systems. Even when the steam is generated at high pressure in a power boiler, reducing valves are interposed between the boiler-main and the steam-heating system to reduce the boiler pressure to the low heating pressure. The average pressure carried in steam radiators is probably about 1 or 2 lb. per sq. in. gage.

Note.—Vacuum Systems (Fig. 526), so called, are those in which a partial vacuum (Sec. 16) is carried in the return piping of the steam-heating system and sometimes even in the radiators. As explained in the following Sec. 598, an automatic trap or valve (Fig. 522) is, ordinarily in a vacuum system, interposed between the outlet of each radiator and the return main. This valve prevents steam from entering the return pipe. Therefore, where such a valve is used, the steam pressure in the radiators of a vacuum system will not decrease to below atmospheric pressure unless the vacuum-return valves leak and thereby entail a constant loss.

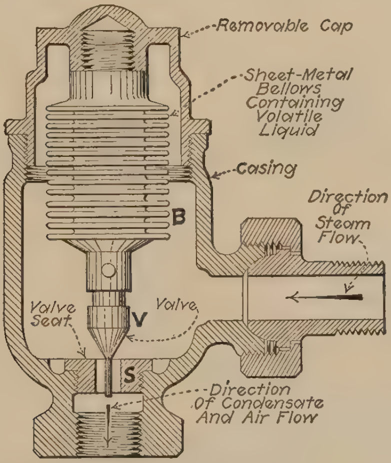

Removable Cap
Sheet-Metal Bellows Containing Volatile Liquid
Casing
Direction Of Steam Flow
B
Valve Seat
Valve
V
S
Direction Of Condensate And Air Flow

Fig. 522.—The *Webster* "*Sylphon*" trap or "trap valve" for steam radiators.

Note.—The Pressure In Exhaust-steam Heating Systems (see following Sec. 598) usually ranges from 1 to 5 lb. per sq. in. gage. A back-pressure valve (*B*, Fig. 523), which is inserted in the engine-exhaust line to the atmosphere, maintains automatically the desired pressure in the heating system. A vacuum heating system operating on exhaust steam insures a small back-pressure on the engines.

NOTE.—THE VARIOUS METHODS OF PIPING (SEC. 596) MAY BE USED FOR UTILIZING STEAM AT ANY OF THE PRESSURES listed above. Also, any combination of piping and steam pressure may be operated either as a gravity-return system or as a forced-return system. Thus the arrangement shown in Fig. 519 might be designated as *a two-pipe, low-pressure, gravity-return, steam-heating system.*

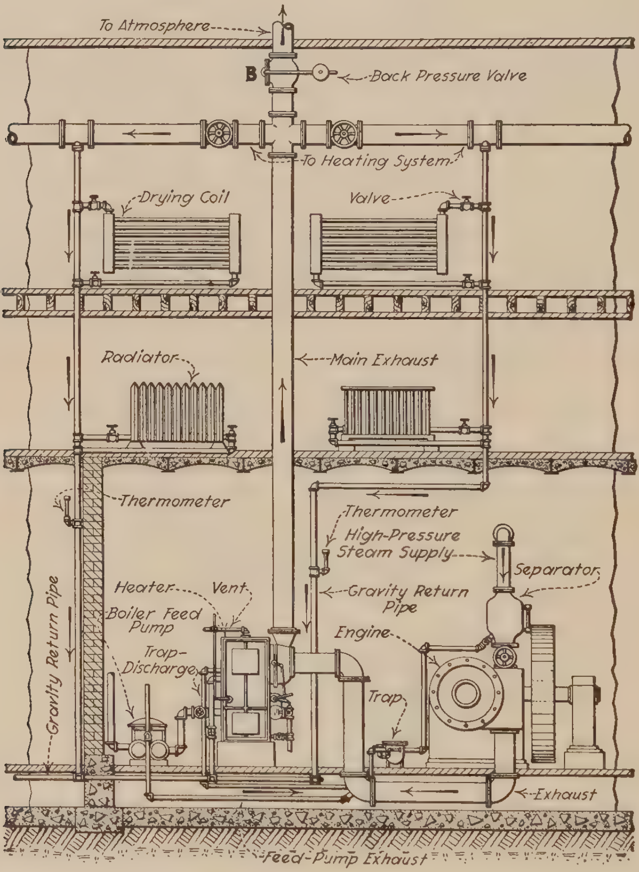
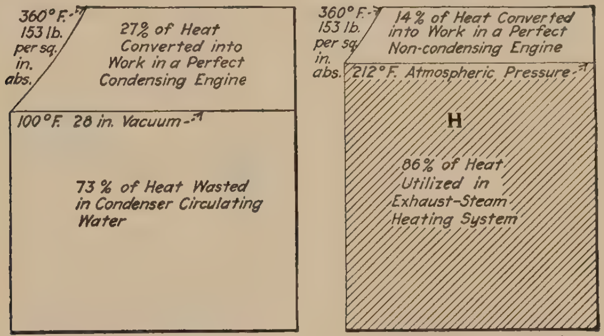


FIG. 523.—Typical exhaust-steam gravity-return heating system. (*Harrison Safety Boiler Works.*)

598. Exhaust Steam, Where Available, Provides A Most Economical Source Of Heat For Building Warming.—About 80 per cent. of the total heat in the steam which is supplied to a non-condensing engine or turbine (Figs. 524 and 525) is wasted in the exhaust if the machine exhausts directly into the atmosphere. Only about 20 per cent. at most of this exhaust steam can be effectively utilized for feed-water heating. Hence, even after the boiler feed water has been heated by exhaust steam up to 212° F., about: 0.80 − (0.20 × 0.80) = 0.64 = 64 per cent. of the entire quantity of heat supplied to the engine is available in remaining exhaust steam for building warming. Thus, steam which has first been passed through an engine or turbine, and made to do all of the work that it can do therein, is, as it exhausts from the non-condensing engine or turbine, almost as effective (80 per cent. of the original heat is in the exhaust steam) for building warming as is high-pressure live steam. In one sense, the engine or tur-


360° F.
153 lb. per sq. in. abs.
27% of Heat Converted into Work in a Perfect Condensing Engine
100° F. 28 in. Vacuum
73% of Heat Wasted in Condenser Circulating Water
360° F.
153 lb. per sq. in. abs.
14% of Heat Converted into Work in a Perfect Non-condensing Engine
212° F. Atmospheric Pressure
H
86% of Heat Utilized in Exhaust-Steam Heating System

I - Condensing Unit II - Non-Condensing Unit

FIG. 524.—Exhaust steam at atmospheric pressure contains an amount of heat, *H*, equal to 80 to 85 per cent. of the total heat of the live steam.

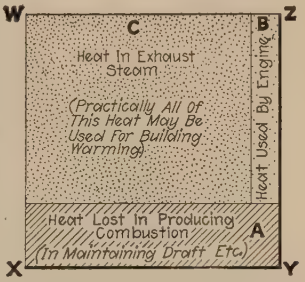

W
Z
C
B
Heat In Exhaust Steam
(Practically All Of This Heat May Be Used For Building Warming)
Heat Used By Engine
Heat Lost In Producing Combustion (In Maintaining Draft Etc.)
A
X
Y

FIG. 525.—Exhaust steam available for heating. (The area *WXYZ* represents the total heat in the coal. The area *B* represents, approximately, the heat used and wasted in the engine. The area *C* represents, approximately, the heat in the exhaust steam, most of which may be utilized in building warming.)

bine acts merely as a reducing valve. Consider the following example:

Example.—From Steam Table 394, 1 lb. of saturated steam at a pressure of 100 lb. per sq. in. gage contains a total of 1,188.8 B.t.u. Also, this 1 lb. of steam, after adiabatic expansion to 3.3. lb. per sq. in. gage, contains a total heat of 1,052 B.t.u. Hence an engine in working the steam from a pressure of 100 lb. per sq. in. gage down to a back pressure of 3.3. lb. per sq. in. gage, could extract only: 1,188.8 − 1,052 = 136.8 *B.t.u. per lb.* from the steam. The greater part of the 1,052 B.t.u. which is in each pound of steam at a pressure of 3.3. lb. per sq. in. gage is usually available for building or other heating.

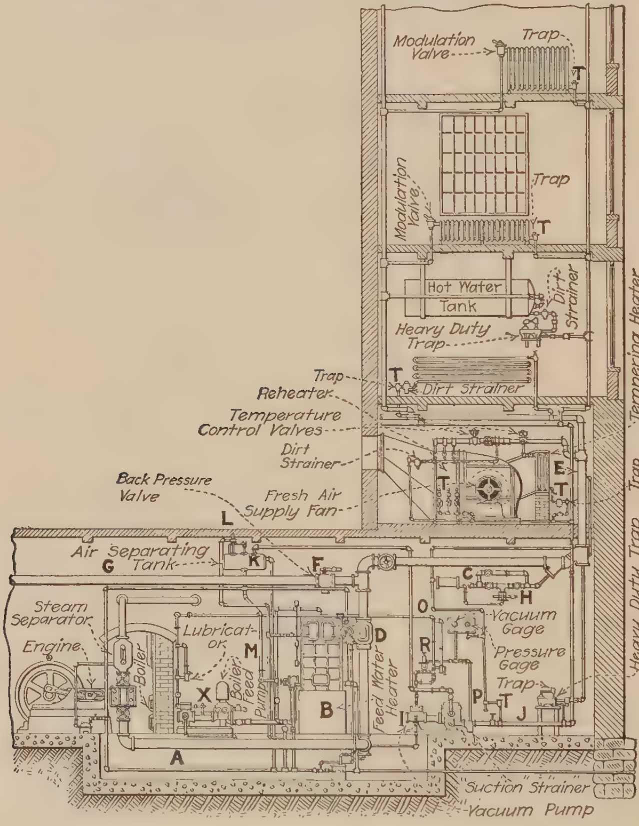


Fig. 526.—Typical (*Webster*) system of piping for exhaust-steam heating.

Explanation —The Operation Of A Typical Exhaust-steam Vacuum-return Heating System (*The Webster System*) will now be explained. Refer to Fig. 526. Steam is exhausted from the main engine through the main exhaust, *A*. It then passes through the oil separator, *D*. There it divides, part passing to the feed-water heater, *B*, and the remainder passing through *C* to the heating main, *E*. The back-pressure valve, *F*, is so adjusted that if an excess of exhaust steam, over that amount required for the heating system, is available, this excess is permitted to escape through the atmospheric exhaust pipe, *G*. If the engine stops, or if the load is so decreased that insufficient exhaust steam is available to produce the desired steam pressure in the heating system, then live steam is admitted directly from the boiler through the pressure-regulating valve, *H*.

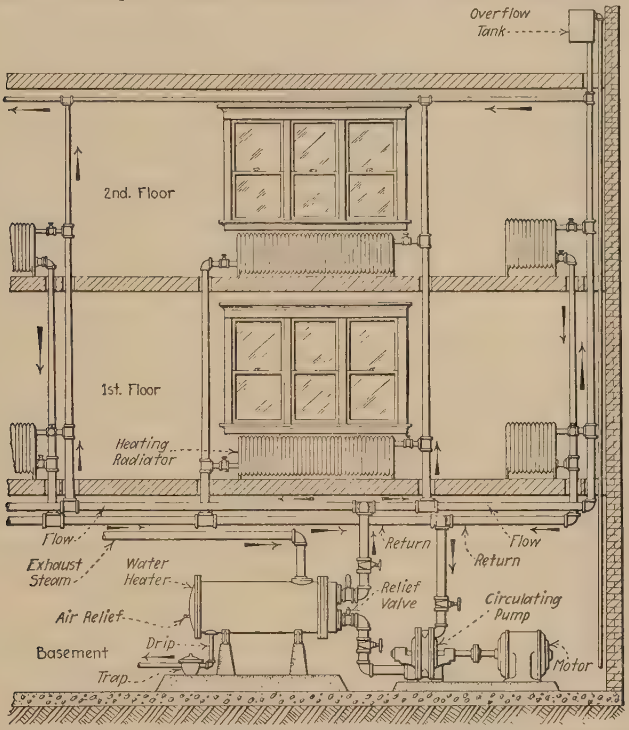


Fig. 527.—Office adjacent to a factory heated by an exhaust-steam hot-water system. The advantages of hot-water heating are under certain conditions realized even though the heat is derived from exhaust steam. (*Whitlock Coil Pipe Co.*)

The vacuum pump, *I*, delivers the condensate and air from the main return, *J*, to the receiver, *K*. The air escapes from *K* through the vent, *L*, and the condensate flows through the loop, *M*, to the feed-water heater, from which it is returned to the boiler by the boiler-feed pump, *X*. The pump governor, *R*, which is connected to the live-steam main through pipe O, and to the return main through pipe P, so operates as to automatically maintain a constant vacuum in the heating-system returns. It is essential that the return side of each radiator be equipped with a trap, T, which will permit water and air to pass, but not steam. Such a trap is shown in Fig. 522.

The trap valve, V (Fig. 522) is shown in the open position. As steam contacts with and heats the sheet-metal bellows, B, which is filled with a volatile liquid, the liquid vaporizes. Then B expands, and closes the valve. When air or water enters the trap, B is thereby cooled. It then contracts, thus opening the valve and permitting the air or water to flow or be pumped out of the radiator. When all of the air and water have escaped, steam will again surround B and the cycle will be repeated.

An exhaust-steam hot-water heating arrangement is shown in Fig. 527.

599. The Area Of The Radiating Surface Required For Warming A Building With Either Direct Steam Or Hot-water Radiators may be computed by the following formula:

$$A = \frac{\mathbf{Q}_T}{K(T_2 - T_1)} \qquad \text{(square feet)} \tag{362}$$

Wherein: A = area, in square feet, of the radiating surface. $\mathbf{Q}_T$ = total heat loss, in B.t.u. per hour, from room as determined by For. (356) or (361). T_1 = temperature of the room, in degrees Fahrenheit. T_2 = average temperature, in degrees Fahrenheit, of the heating medium within the radiator. K = heat emitted, in B.t.u. per square foot per degree Fahrenheit temperature difference between the heating medium within the radiator and the room; for values of K, see Table 600 and Fig. 517.

Derivation.—As explained in preceding Sec. 561, to maintain the room temperature constant, the heat given off by the radiators in the room must be equal to the heat loss from the room, that is:

$$\textit{Heat given off by the radiators} = \mathbf{Q}_T \qquad \text{(B.t.u. per hr.)} \tag{363}$$

Now, (*the total heat given off by any radiator*) = (*B.t.u. given off per sq. ft. per hr. per deg. Fahr temperature difference*) × (*difference between room temperature and the heating medium within the radiator*) × (*area of the radiator surface in sq. ft.*). Using the symbols specified above instead of words, the preceding statement becomes:

$$\mathbf{Q}_T = K(T_2 - T_1)A \qquad \text{(B.t.u. per hr.)} \tag{364}$$

Transposing, there results·

$$A = \frac{\mathbf{Q}_T}{K(T_2 - T_1)} \qquad \text{(square feet)} \tag{365}$$

Which is the same as For. (362)

Note.—Average Inside-radiator-temperature Values As Ordinarily Used In Practice in computing required-radiating area are:

(1) *Steam*, 220° F. (2) *Hot water:* open tank system, 170° F.; closed tank system, 210° F.

EXAMPLE.—How many square feet of radiating surface would be required, using 2-column, 44-in. radiators, to maintain the temperature of the room which is specified in Example under Sec. 574, at a temperature of 70° F. with a steam-heating system? With an open-tank hot-water system? SOLUTION.—By Example, Sec. 574, $Q_T = 28{,}920$ *B.t.u. per hr.* From Fig. 517, K for a 2-column, 44-in. radiator = 1.6. Therefore, by For. (362), *the area of radiating surface for steam heating*, $A = Q_T/K(T_2 - T_1) = 28{,}920 \div 1.6(220 - 70) = 120$ *sq. ft. For hot water*, $A = 28{,}920 \div 1.6(170 - 70) = 180$ *sq. ft.*

600. Table Of Coefficients Of Heat Transmission From Radiators (either hot-water or steam) of various types. This data is based on a temperature difference between the radiator and the air of about 150° F. which represents ordinary conditions. The variation of the coefficients with the height of cast-iron radiators is shown in Fig. 517. (From HEATING AND VENTILATION by Allen and Walker.)

Radiator		K (For. 362) B.t.u. per square foot per hour per degree difference in temperature
Type	Description	
CAST IRON, HEIGHT 38 IN.	One-column	1.75
	Two-column	1.65
	Three-column	1.55
	Four-column	1.45
WALL COIL	Heating surface 5 sq. ft., long side vertical	1.92
	Heating surface 5 sq. ft., long side horizontal	2.11
	Heating surface 7 sq. ft., long side vertical	1.70
	Heating surface 7 sq. ft., long side horizontal	1.92
	Heating surface 9 sq. ft., long side vertical	1.77
	Heating surface 9 sq. ft., long side horizontal	1.98
PIPE COIL	Single horizontal pipe	2.65
	Single vertical pipe	2.55
	Pipe coil 4 pipes high	2.48
	Pipe coil 6 pipes high	2.30
	Pipe coil 9 pipes high	2.12

601. The Requisite Grate Area For Steam And Hot-water Boilers For Building-warming Service may be computed by the following formula:

$$A = \frac{1.25\mathbf{Q}_T}{\mathbf{HWE}} \qquad \text{(square feet)} \tag{366}$$

Wherein: A = grate area of steam or hot-water boiler, in square feet. $\mathbf{Q}_T$ = heat loss, in British thermal units per hour, from the building as determined by For. (356) or (361). $\mathbf{H}$ = heat value of the coal, in British thermal units per pound; see Table 451. $\mathbf{W}$ = weight of coal burned, in pounds per hour per square foot of grate surface. $\mathbf{E}$ = boiler, furnace, and grate efficiency, expressed as a percentage.

The Derivation Of For. (366) is similar to that of For. (372), which is presented under Sec. 612. In For. (366), it is assumed that 20 per cent. of the heat in the steam which is available for warming the building is lost in the piping. For values of **H**, see Table 451. **W**, will, for 8-hr. firing periods, vary from about 4 to 8 lb. per hr. per sq. ft. of grate area. For boilers with grate areas which exceed about 20 sq. ft., a rate of combustion of 10 to 15 lb. per hr. per sq. ft. of grate area can be maintained by constant attendance with short firing intervals. Approximate values of **E** may be obtained from Table 580.

Note.—Boiler Capacities May Be Stated In Terms Of The Boiler Horsepower. By definition (see Sec. 500): 1 *boiler hp. is equal to* 34.5 *lb. of water evaporated per hour, from and at* 212° *F.* Since the latent heat of steam at 212° F. is (Table 394,) 970.4 B.t.u. per lb., 1 *boiler hp. is equivalent to:* 970.4 × 34.5 = 33,479 *B.t.u. per hr.* Also, since 1 sq. ft. of a standard cast-iron steam radiator has, at a temperature of 220° F., a heat emission of about 250 B.t.u. per sq. ft. per hr., 1 *boiler hp. will supply:* 33,479 ÷ 250 = 133.8 *sq. ft. of steam radiation,* or: 33,479 ÷ 150 = 223.1 *sq. ft. of hot-water radiation.* In using these values for computing the boiler-horsepower rating of a boiler to supply a given area of radiation, allowance must be made for the loss of heat in the piping. This is usually done by adding about 25 per cent. of the total radiator area.

Example.—What grate area will be required for a steam boiler which is to heat a building having a heat loss of 160,000 B.t.u. per hr., if 6 lb. of Illinois soft coal is to be burned each hour on each square foot of grate surface? The boiler-and-grate efficiency is assumed to be 70 per cent. Solution.—By Table 451, *the heat value of Illinois soft coal* = 10,000 *B.t.u. per lb.* By For. (366), *the required grate area,* A, = 1.25 $\mathbf{Q}_T/\mathbf{HWE}$ = 1.25 × 160,000 ÷ (10,000 × 6 × 70) = 4.76 *sq. ft.*

602. Building Warming By Indirect Heating (Fig. 528) consists of heating air, by causing it to pass over a hot metallic surface, and then leading the air through suitable ducts to the room which is to be heated. Thus in indirect heating, air is the medium whereby the heat is transmitted from the hot metallic surface to the room.

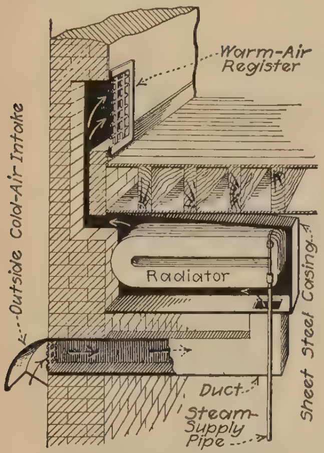


Fig. 528.—Diagram of elementary indirect heating system.

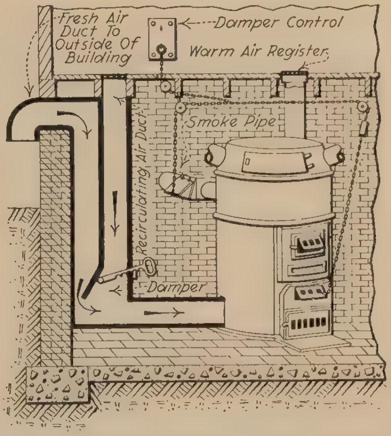


Fig. 529.—Warm-air furnace with cold-air ducts so constructed that a portion of the air may be recirculated, and the remainder taken from the outside.

603. The Two Principal Methods Of Indirect Heating are: (1) *The gravity system,* (Fig. 529) wherein the air flow is produced by convection (Div. 5); the gravity system is usually employed in conjunction with a warm-air furnace (Sec. 605). (2) *The hot-blast or plenum system* (Fig. 538), wherein the air flow is accelerated by power-driven blowers or fans, *F*. In the hot-blast system (Sec. 607), the air is passed over a heater constructed of pipes, tubes, or cast-iron sections, which contain steam, hot water, or hot gas—or an electric heater might be used.

604. A Pipeless Warm-air Furnace (Figs. 127 and 530) circulates the air by convection. With a fire in the fire pot, *P*, (Fig. 530) the air in the chamber *C* upon being heated, expands and is pushed upward into the room by the now-heavier cold air in the outer casing. The cold air is thus drawn from the room and replaced by the heated air, which warms the room. The circulation of the warm and cool air through the building is represented by the arrows in Fig. 410.

605. The Usual Type Of Warm-air Furnace (Fig. 531) has *warm-air pipes* which conduct the warm air to the *warm-air*

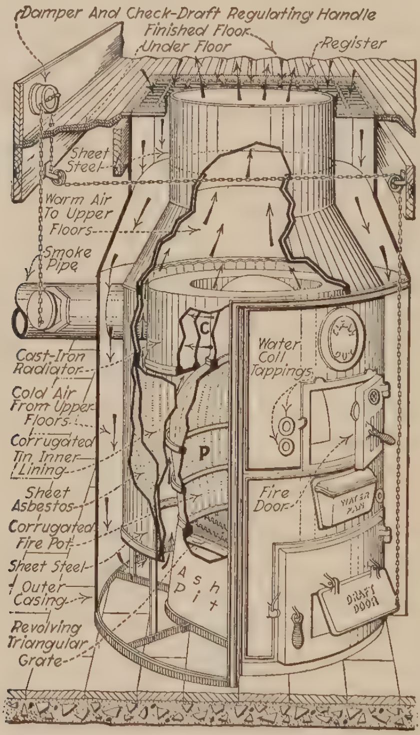


Fig. 530.—A pipeless warm-air furnace.

registers located in the various rooms. The method of heating the air is the same as that of the pipeless furnace (Sec. 604). In this Fig. 531 installation, however, the cold-air supply is drawn from outside the building through a duct. If desired, however, the air from the building may be drawn into the heater through the recirculating duct.

606. The Location Of The Warm- And Cold-air Registers Within A Room should be given particular attention. Experimental results of air-passage through a room with various locations of the warm- and cold-air registers are shown graphically in Figs. 532, 533, 534, 535, 536 and 537. (Carpenter Heating And Ventilating.) Fig. 537 shows the preferable arrangement. It follows that an improper location of the registers may result in poor ventilation. The ventilation will be poor if the air passes through the room above the "*breathing line*," because then the fresh air cannot be utilized by the occupants.

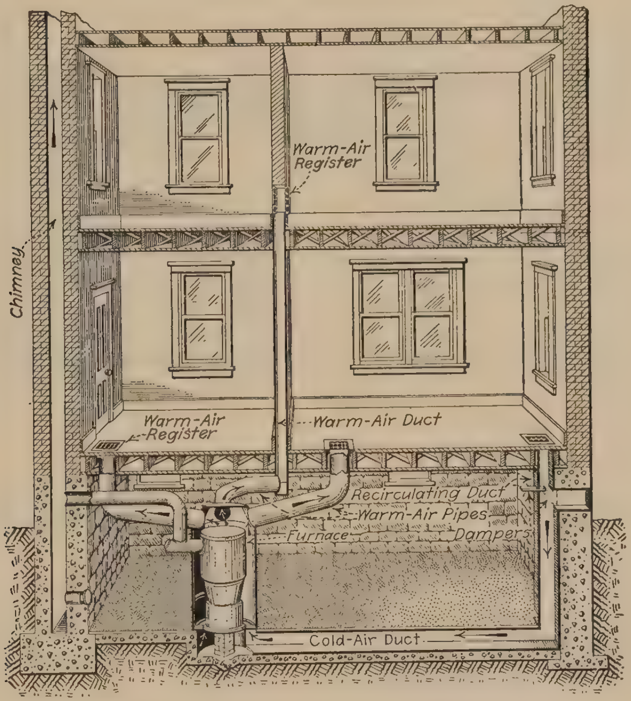


Fig. 531.—A dwelling warmed by a warm-air furnace.

607. The Hot-blast Or Plenum System Of Building Warming (Fig. 538) is particularly adaptable for warming such rooms as are to be occupied by a large number of persons, thus necessitating the introduction of a considerable quantity of air for ventilation. The cold air, which is taken from the outside (Fig. 538), first passes through a radiator or tempering stack, T.

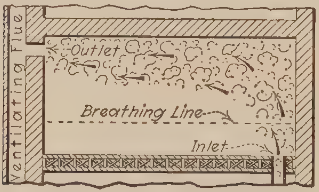


Fig. 532.—Room ventilation—warm air introduced at bottom, discharged at top.

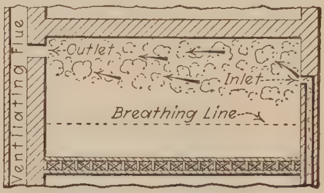


Fig. 533.—Air introduced on side, discharged at top.

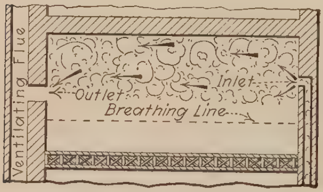


Fig. 534.—Air introduced on side, discharged at opposite side.

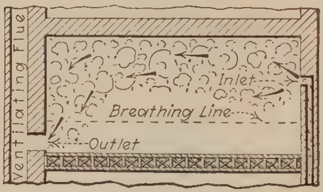


Fig. 535.—Air admitted on side, discharged near bottom.

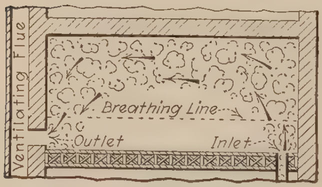


Fig. 536.—Air admitted at bottom, discharged near bottom.

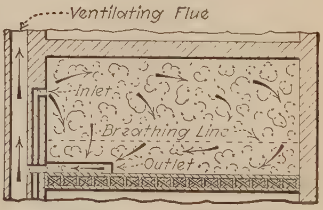


Fig. 537.—Air admitted near top, discharged near bottom.

Explanation.—In passing through T, the air is warmed so that in cold weather there will be no tendency to freeze the air-washing and humidifying water W. Another function of T is that, by raising the temperature of the air before the air passes through W, it causes the air to absorb more moisture than it would if it were cold when passing through W. Thereby the relative humidity (Sec. 331) of the air in the rooms is increased. The air now passes from W and into the power-driven blower F, by which it is forced through the main heating stack or radiator, H, the warm-air duct, A, and into the room or rooms to be heated. The air, which is cooled in the room, passes from the room to the outside of the building through the cold-air register C. Supplementary steam-heated wall radiators are employed in this installation to heat the cold air which filters through the windows, thus keeping the floor warm. A by-pass damper, *P*, is provided for controlling the room temperature. This it does by permitting the introduction of "tempered" cool air when necessary. These dampers are controlled pneumatically by the action of the automatic thermostat, *G*.

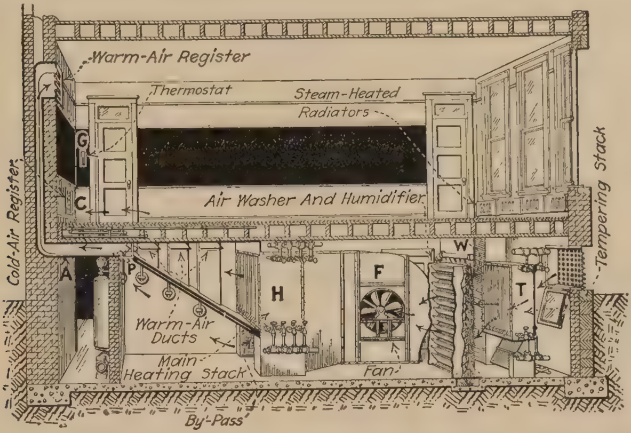


FIG. 538.—Plenum system of school room heating and ventilating. (*American Radiator Co.*)

608. The Quantity Of Air Required For Building Warming may be computed by the following formula:

$$(367) \qquad V = \frac{55Q_T}{(T_1 - T_2)} \qquad \text{(cu. ft. per hr.)}$$

Wherein: V = volume of air, in cubic feet per hour, required to warm the room. Q_T = heat loss from building, in British thermal units per hour, as computed by For. (356) or (361). T_1 = temperature of air, in degrees Fahrenheit leaving the warm-air register. T_2 = room temperature, in degrees Fahrenheit.

DERIVATION.—By Sec. 573, 1 B.t.u. will raise the temperature of 55 cu. ft. of air 1° F. Hence, $V \div 55$ = quantity of heat, in British thermal units, required to raise V cubic feet of air 1° F., conversely, $V \div 55$ = quantity of heat, in British thermal units, given off by V cubic feet when the temperature decreases 1° F. If air enters the room at a temperature of T_1 degrees Fahrenheit and leaves at T_2 degrees Fahrenheit, the temperature decrease is $(T_1 - T_2)$ degrees Fahrenheit. Therefore, $(V \div 55) \times (T_1 - T_2)$ = *quantity of heat given off by V cubic feet of air when* *it enters at T_1 degrees Fahrenheit and leaves at T_2 degrees Fahrenheit.* The quantity of heat supplied to the room per hour to maintain a constant temperature therein, must (Sec. 561) be equal to the quantity of heat, Q_T, lost from the room per hour. Or,

$$\frac{V}{55}(T_1 - T_2) = Q_T \qquad \text{(B.t.u. per hr.)} \tag{368}$$

Transposing For. (368):

$$V = \frac{55Q_T}{(T_1 - T_2)} \qquad \text{(cu. ft. per hr.)} \tag{369}$$

Which is identical with For. (367).

Example.—If the temperature of the air leaving the register is 130° F., how many cubic feet of air will be required per hour to maintain the room of the Example under Sec. 574 at a temperature of 70° F.? Solution.—By For. (367), *the quantity of air required,* $V = 55Q_T/(T_1 - T_2) = 55 \times 28{,}920 \div (130 - 70) = 26{,}510$ *cu. ft. per hr.*

609. The Requisite Temperature Of The Incoming Air To A Room may be computed by the following formula. This formula is obtained by a transposition of For. (367).

$$T_1 = \frac{55Q_T}{V} + T_2 \qquad \text{(degrees Fahrenheit)} \tag{370}$$

Wherein all symbols are as explained under For. (367).

Example.—A certain school room, which is to be warmed by warm air, has a heat loss of 50,000 B.t.u. per hr. when the room temperature is 70° F. It is to be occupied by 30 students. What should be the temperature of the incoming air to maintain the room temperature at 70° F.? Solution.—*The quantity of fresh air required for ventilation* $= 30 \times 1{,}800 = 54{,}000$ *cu. ft. per hr.* If each person emits (Sec. 559) 400 B.t.u. per hr., *the net heat which must be supplied* $= 50{,}000 - (30 \times 400) = 38{,}000$ *B.t.u. per hr.* By For. (370), *the temperature of the incoming air,* $T_1 = (55\ Q_T/V) + T_2 = (55 \times 38{,}000 \div 54{,}000) + 70 = 108.7°$ F.

610. Either All Or A Portion Of The Air In An Indirect Heating System May Be Taken From The Outside, It May All Be Recirculated.—In warming rooms which are to be occupied by only a few people, the infiltration air (Sec. 568) may be sufficient for ventilation purposes. In such cases all of the air which passes through the furnace may be taken from within the building as in Figs. 127, 410 and 530. If infiltration is insufficient for proper ventilation, all of the air may be taken from the outside, as in Figs. 528 and 538. Or, as shown in Fig. 529, only a part of the air may be taken from the outside. As will be demonstrated by the following example, a large heat-saving may sometimes be effected by recirculating a portion of the air.

NOTE.—THE MOST ECONOMICAL TEMPERATURE FOR THE AIR AS IT ENTERS THE ROOM FROM A WARM-AIR REGISTER has been found by experience to be between 130 and 140° F.

EXAMPLE.—An office room occupied by 10 persons has, with a 70° F. inside temperature and 0° F. outside temperature, a heat loss of 36,000 B.t.u. per hr. The temperature of the air issuing from the register is to be 140° F. Under these conditions, how much fresh air should be brought in from the outside per hour? How much may be recirculated, and what is the heat-saving effected by such recirculation?

SOLUTION.—By Sec. 576, allowing for the heat given off by the 10 people in the room, $36{,}000 - (10 \times 400) = 32{,}000$ *B.t.u. per hr.* must be supplied the room by artificial means to maintain a 70° F. room temperature. By Sec. 573, $10 \times 1{,}800 = 18{,}000$ *cu. ft. of air per hr.* which should be brought in from the outside for ventilation. *The total quantity of air to be circulated is*, by For. (367), $V = 55\,Q_T/(T_1 - T_2) = 55 \times 32{,}000 \div (140 - 70) = 25{,}150$ *cu. ft. per hr.* Therefore, $(25{,}150 - 18{,}000) = 7{,}150$ *cu. ft. per hr.* can be recirculated without impairing the ventilation. Since this 7,150 cu. ft. per hr. leaves the room and enters the furnace at 70° F., it is only necessary to supply sufficient heat to it, to raise its temperature through $(140 - 70) = 70°$ F., whereas if it were taken from the outside a temperature increase of $(140 - 0) = 140°$ F. would be required. Therefore, *a saving of* $(7{,}150 \div 55) \times (140 - 70) = 9{,}100$ *B.t.u. per hr.*, is, in this instance, effected by the recirculation. Without recirculating any air there would be required $(25{,}150/55) \times 140 = 64{,}108$ *B.t.u. per hr.* Hence, the *saving*, in this instance, $= 9{,}100 \div 64{,}108 = 0.142$ or 14.2 *per cent.*

611. The Ratio Between The Quantity Of Heat Supplied To The Warming-air And Q_T may be determined by:

$$(371) \qquad X = \frac{Q_F}{Q_T} = \frac{(T_F - T_O)V_O + (T_F - T_2)V_C}{(V_O + V_C)(T_1 - T_2)} \qquad \text{(number)}$$

Wherein all temperatures are expressed in degrees Fahrenheit and: Q_T = quantity of heat, in British thermal units per hour, lost from the room as computed by For. (356) or (361). X = ratio between the quantity of heat Q_F, supplied by the furnace to the warming-air and Q_T. Q_F = heat, in British thermal units per hour, supplied to the warming-air by the furnace. T_F = temperature of the air leaving the furnace cap. T_O = temperature of the outside air. T_2 = room temperature. T_1 = temperature of the air leaving the warm-air register. V_O = quantity of air, in cubic feet per hour, taken from the outside. V_C = quantity of air, in cubic feet per hour, which is recirculated.

Derivation.—Since (Sec. 573) it requires 0.02 B.t.u. to raise the temperature of 1 cu. ft. of air 1° F., *the total quantity of heat, in British thermal units per hour, supplied by the furnace to the air which is brought in from the outside* = $0.02(T_F - T_O)V_O$. *The heat, in British thermal units per hour, supplied by the furnace to the air which is recirculated* = $0.02(T_F - T_2)V_C$. Then, *the total heat*, Q_F, *in British thermal units per hour, supplied by the furnace to the warming-air:* $0.02(T_F - T_O)V_O + 0.02(T_F - T_2)V_C$. The *total quantity of air, in cubic feet per hour, supplied to the room* = $(V_O + V_C)$. The total heat, supplied to the room must, to maintain a constant temperature therein, be equal to the heat lost by the conduction through partitions and the infiltration (Sec. 561), which is Q_T. By definition, $X = Q_F/Q_T = [0.02(T_F - T_O)V_O + 0.02(T_F - T_2)V_C]/(V_O + V_C)(T_1 - T_2)0.02$, which, when simplified becomes For. (371).

Note.—The Maximum Temperature Conditions Usually Assumed In Warm-air Furnace Computations for substitution in the above formula are: (1) *Temperature of air leaving furnace cap*, T_F = 180° *F*. (2) *Temperature of outside air*, T_O = 0° *F*. (3) *Room temperature*, T_2 = 70° *F*. (4) *Temperature of air leaving warm-air register*, T_1 = 140° *F*.

612. The Requisite Grate Area For Warm-air-furnace Building Warming is dependent upon: (1) *Inside-outside temperature difference.* (2) *Temperature difference between the air leaving the furnace cap and the air leaving the warm-air register.* (3) *Quantity of air recirculated.* (4) *Heat value of the coal.* (5) *Furnace efficiency.* (6) *Rate of combustion.* The grate area which will be required for warming any room or building may be computed by the following formula:

$$A = \frac{X\mathbf{Q}_T}{\mathbf{HWE}} \quad \text{(sq. ft.)} \tag{372}$$

Wherein: A = grate area, in square feet. X = ratio between the quantity of heat supplied to the warming-air and the heat given up to the room or building by the warming-air as determined by For. (371). $\mathbf{Q}_T$ = heat loss, in British thermal units per hour, from the room or building, as determined by For. (356) or (361). $\mathbf{W}$ = weight of the coal burned, in pounds per hour per square foot of grate surface. $\mathbf{E}$ = furnace-and-grate efficiency expressed decimally.

H = heat value of the coal, from Table 451, in British thermal units per pound.

DERIVATION.—The total heat generated per hour by the combustion of the fuel in the furnace is equal to: (*Area of the grate in square feet*) × (*Number of pounds of coal burned per hour on each square foot of grate surface*) × (*Heat value of the coal in British thermal units per pound*). And this multiplied by the fractional part of the heat, **E**, which is transmitted to the warming-air (furnace-and-grate efficiency) results in *the total heat*, Q_F, *in British thermal units per hour, supplied to the warming-air by the furnace.* Expressing the above symbolically, wherein all symbols are as specified under For. (372):

$$Q_F = A\mathbf{HWE} \qquad \text{(B.t.u. per hr.)} \tag{373}$$

Transposing For. (373):

$$A = \frac{Q_F}{\mathbf{HWE}} \qquad \text{(square feet)} \tag{374}$$

By For. (371), $Q_F = XQ_T$. Substituting this value of Q_F in For. (374):

$$A = \frac{XQ_T}{\mathbf{HWE}} \qquad \text{(square feet)} \tag{375}$$

Which is identical with For. (372).

NOTE.—VALUES USUALLY ASSUMED IN WARM-AIR FURNACE COMPUTATIONS for substitution in For. (372) are: (1) *Heat value of the coal (anthracite)*, **H**, = 12,000 *B.t.u. per lb.;* also see Table 451. (2) *Weight of coal burned*, **W**, *usual rate* = 4 *lb. per hr. per sq. ft. of grate surface; maximum rate in extremely cold weather* = 8 *lb. per hr. per sq. ft. of grate surface.* (3) *Furnace-and-grate efficiency*, **E**, = 60 *to* 70 *per cent.;* see Table 580.

EXAMPLE.—Basing the computation on the usual assumptions, what grate area will be required to warm a building which has a heat loss of 101,800 B.t.u. per hr., if 25 per cent. of the air is to be recirculated?

SOLUTION.—By For. (369), *the quantity of air required per hour* = $V = 55\ Q_T/(T_1 - T_2) = 55 \times 101{,}800 \div (140 - 70) = 80{,}000$ *cu. ft. The quantity of air recirculated*, $V_C = 0.25 \times 80{,}000 = 20{,}000$ *cu. ft. per hr.* Therefore, *the quantity of air which must be brought in from the outside*, $V_O = 80{,}000 - 20{,}000 = 60{,}000$ *cu. ft. per hr.* By For. (371), $X = [(T_F - T_O)V_O + (T_F - T_2)V_C]/[(V_O + V_C)(T_1 - T_2)] = [(180 - 0)60{,}000 + (180 - 70)20{,}000] \div 80{,}000(140 - 70) = 2.3$. By For. (372), *the required grate area*, $A = XQ_T/\mathbf{HWE} = 2.3 \times 101{,}800 \div (12{,}000 \times 8 \times 0.65) = 3.75$ *sq. ft.*

613. The Proper Size Of The Air Ducts And The Registers may be computed upon the following basis: It is ordinarily assumed that the air velocities in the warm-air ducts in gravity warm-air heating systems are: (1) *First floor*, 4 *ft. per sec.* (2) *Second floor*, 6 *ft. per sec.* (3) *Third floor*, 8 *ft. per sec.* Therefore, the size of the warm-air duct may be computed by:

$$A = \frac{V}{3{,}600v} \qquad \text{(square feet)} \tag{376}$$

Wherein: A = area, in square feet, of warm-air duct. v = velocity, as above specified, of air through duct, in feet per second. V = volume of air, in cubic feet per hour, as computed by For. (367). 3,600 = number of seconds in one hour.

Note.—The Overall Area Of The Warm-air Registers should be from about 1.5 to 2 times the area of the warm-air duct, depending upon the amount of free area of the register. The areas of the cold-air duct and register should be about 0.75 times those of the warm-air duct and register, respectively.

Note.—The Allowable Air Velocity For Forced-draft Warm-air Heating (Sec. 607) may, if the warm-air registers are placed above the heads of the occupants, be as high as 10 to 12 ft. per sec.

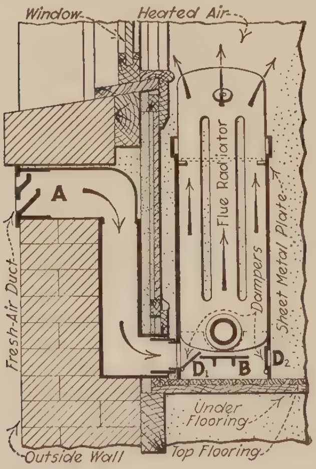


Fig. 539—Diagram of direct-indirect heating radiator.

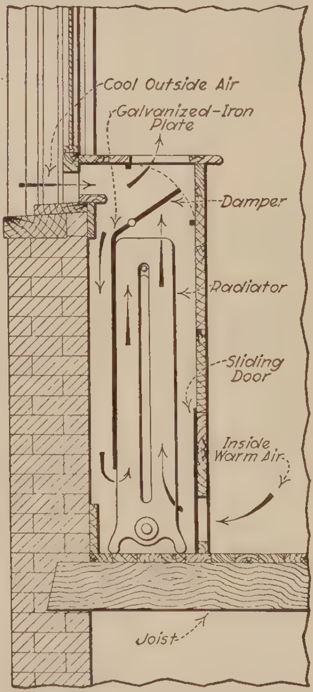


Fig. 540.—Showing method of direct-indirect heating. Outside air may be shut off by lowering window sash.

614. The Direct-indirect Method Of Building Warming (Figs. 539 and 540) provides for the circulation of either inside or outside air through a radiator of the flue type. The radiator is connected to the outside air by a cold-air duct, *A* (Fig. 539) and to the inside air by a box base, *B*. The surface of the radiator which is exposed to the room gives off heat by radiation and convection just as does a direct-heating radiator. The cold-air which enters from the outside passes, by convection, up through the vertical flues, thus supplying heat to the room in the same manner as an indirect heating system. By adjustment of the dampers, D_1 and D_2, the proportionate amounts of outside and inside air which are circulated may be varied as desired.

615. The Rate Of Heat Emission Of An Electric Heater (Fig. 494) may be computed by the following:

$$Q = Watts \times 3.415 \qquad \text{(B.t.u. per hr.)} \qquad (377)$$

Wherein: **Q** = heat given off by heater, in British thermal units per hour. Electric heaters are, when considered upon the basis of the proportion of the electrical-energy input to the heater to its heat-energy output, 100 per cent. efficient, since all of the electrical energy consumed is transformed into heat energy.

EXAMPLE.—Since the room of Fig. 497 requires 28,920 B.t.u. per hr. to maintain it at 70° F., the rate of electrical energy expenditure or the power necessary to thus maintain it at 70° F. would be—transposing For. (377): $Watts = Q/3.415 = 28{,}920 \div 3.415 = 8{,}468$ *watts*.

QUESTIONS ON DIVISION 17

1. Why is artificial building warming necessary?
2. What are the principal factors which must be considered in planning a heating system?
3. Name three distinct sources of building warming. Which is the most important source?
4. Name the three methods of transference whereby heat may be transmitted to a room.
5. If a constant temperature is maintained within a room, to what must the rate of heat-supply thereto be equivalent?
6. What is the procedure in designing a heating installation for a room or building?
7. In what three ways is heat lost from a room or building?
8. What factors determine the quantity of heat which is lost from a building by conduction?
9. What are the usual inside-outside temperature-difference assumptions which are made in building-warming computations?
10. What are the factors which determine the infiltration heat loss from a room?
11. Explain how the direction of exposure affects the loss of heat from a building. What method is used to compute the heat loss due to exposure?

12. How many British thermal units of heat are required to raise the temperature of 1 cu. ft. of air 1° F.?

13. What is the rate of fresh-air supply which should be allowed for each occupant of a room?

14 Derive the *general formula* for computing the total heat loss from a room.

15. Derive Carpenter's formula for heat loss.

16. What is the maximum percentage variation which may be expected between results as obtained by the application of the *general* and *Carpenter's* formula to the same building?

17. What is the rate of heat supply to a building by each occupant? By each lighted electric lamp? By each motor?

18. Explain the effect of humidity on the comfortableness of a room. What should be the relative humidity within a room?

19. Name several ways by which moisture may be supplied to a room.

20. What are the principal methods of warming buildings? Define each.

21. Name the more common types of apparatus which are used for building warming.

22. Give a graphical statement of steam and hot-water heating-plant efficiency.

23. Give a summary of the applications, advantages and disadvantages of the various methods of building warming.

24. What is the principal means by which heat is transmitted to a room by an open grate fireplace? By a stove?

25. Explain by a sketch an economical method of fireproofing the adjacent surroundings of a stove which is located within a wooden building.

26. What are some of the advantages which hot-water and steam-heating systems have as compared to warm-air? What are some of the disadvantages?

27. What two systems may be employed in hot-water building warming? For what condition is each system applicable?

28. Explain with a sketch the principle of the gravity hot-water heating system.

29. Name three methods of piping which are employed in hot-water heating. Make a sketch of each.

30. Why is an expansion tank necessary in a hot-water system? Explain two methods of expansion tank operation and give the usual average radiator temperature employed with each.

31. In what three ways may direct steam-heating systems be classified?

32. How may the condensate be returned to the boiler?

33. Name three methods of piping which are employed in steam heating. Make a sketch of each.

34. Give the pressure-classification limits of steam-heating systems. What is the average steam pressure, in pounds per square inch, within direct-heating steam radiators?

35. Define the *vacuum system* of steam heating.

36. Why is it frequently economical to employ exhaust steam for building warming?

37 Derive the formula for computing the required radiating surface for warming a building with direct steam or hot-water radiators. Derive the formula for the required grate area.

38. Draw a sketch of and explain each of the two principal methods of indirect heating.

39. For what condition is each method applicable?

40. Derive the formula for computing the quantity of air required for building warming. What is the most economical value at which to maintain the temperature of the air leaving hot-air register?

41. Explain with a numerical example how a heat saving is effected by recirculation.

42. Derive the formula for obtaining the requisite grate area for warm-air furnace heating

43. Draw a sketch of, and explain the direct-indirect method of building warming.

44. Give the formula for computing the quantity of heat emitted by an electric heater.

PROBLEMS ON DIVISION 17

1. The living room of a residence is 14 ft. wide, by 18 ft. long, by 10 ft. high. The room has a southeast exposure. There is 100 sq. ft. of window surface. Assuming an inside-outside temperature difference of 70° F., what is the hourly heat loss from the room? (Use Carpenter's formula.)

2. What quantity of heat will be required to raise the temperature of 30,000 cu. ft. of air from 0° F. to 70° F.?

3. What quantity of heat should be allowed for warming the ventilation air for 150 people?

4. A second-story office room is 20 ft. by 20 ft. by 10 ft. For how many persons would the infiltration air provide sufficient ventilation?

5. Forty persons are working in a room of a textile mill which contains a line shaft to which 75 hp. is supplied. The room is lighted by sixteen 100-watt electric lamps. What will be the rate of heat supply to the room per hour by these factors?

6. A warm-air-furnace heating installation has an overall efficiency of 55 per cent. The hourly heat loss from the building is 50,000 B.t.u. How much 11,500-B.t.u. coal must be burned per hour to supply this heat loss?

7. The total heat loss from a building is 158,000 B.t.u. per hr. How much steam-radiator surface will be required to maintain a constant temperature therein, if steam at a pressure of 2.5 lb. per sq. in. gage, in 4-column 44-in. radiators, is used for warming?

8. What grate area would be required for the boiler to warm the building in Prob. 7, if the boiler-and-grate efficiency is 69 per cent., and if 7 lb. of coal which has a heating value of 12,500 B.t.u. per lb. are burned per hour on each square foot?

9. What should be the boiler-horsepower rating of the boiler to warm the building in Prob. 8?

10. What volume of air will be required per hour to warm a building which has a total hourly heat loss of 70,000 B.t.u., if the temperatures of the air at the warm-air and cold-air registers are, respectively, 135° F. and 65° F.?

11. If 20 per cent. of the air required for warming the building in Prob. 10 is recirculated, what is the ratio between the quantity of heat supplied to the warming air and that which is required to maintain constant room temperature? The temperature of the outside air is 0° F. and that of the air leaving the furnace cap is 180° F.

12. What grate area will the warm-air furnace of Prob. 11 require if 8 lb. of 11,000-B.t.u. coal is to be burned per square foot of grate surface per hour? Assume a furnace-and-grate efficiency of 65 per cent.

DIVISION 18

REFRIGERATION

616. Refrigeration Is In General The Process Of Cooling Bodies or, more specifically, it is the process of keeping the temperature below that of the atmosphere. But, since cold is just the absence of heat, refrigeration may be defined as the process of extracting heat. By this latter definition, it is apparent that refrigeration is not a science by itself but is merely a division of heat engineering. Consequently, it utilizes the same general laws that apply to steam engineering, heating and ventilating, and all the other branches of heat engineering. In studying the subject of refrigeration, it is desirable that the reader connect it with the fundamental principles of heat which were discussed in the preceding divisions of this book. If the subject of refrigeration is studied in this manner (by applying the fundamental principles of heat) it can be easily mastered.

NOTE.—REFRIGERATION IS JUST THE REVERSE PROCESS OF HEATING AND THEY BOTH OCCUR AT THE SAME TIME.—The radiator (Sec. 590) which is at a relatively high temperature, in a room heats the room but at the same time the room cools or refrigerates the hot water or steam in the radiator. This, however, is called a heating process because the object of the radiator is to heat the room. Now the cooling coil in a cold-storage room of a refrigerating plant cools the room, but the room and its contents heat the fluid in the cooling coil. In this case the process is the reverse of that which occurs in the heating of the room by the radiator. It is called a refrigeration process because its object is to cool the room and its contents.

617. Refrigeration Is Used In All Industries Where The Cooling Or Freezing Of Substances Is Desired.—It is chiefly used, however, for: (1) *Preserving foods.* (2) *Providing cold drinks and foods.* (3) *Cooling air.* These three uses are probably known to every one. It is almost universally known that trains are equipped with refrigerated cars (Fig. 541) for the shipment of perishable foods; that ships (Fig. 542) are equipped in a similar manner with refrigeration plants; that almost every home has an ice-box (Fig. 543) for cooling drinks and foods; and, that in the summer time theaters (Fig. 544) and other large buildings are supplied with cooled air.

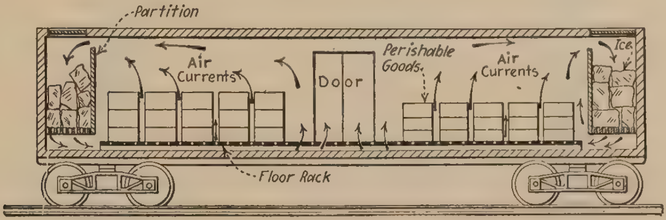


FIG. 541.—Ice-cooled refrigerator car.

NOTE.—BESIDES THE ABOVE COMMONLY KNOWN USES OF REFRIGERATION THERE ARE MANY OTHERS, not so commonly known. Examples are: the use of refrigeration for the removal of certain paraffin products in the refining of oils; its use in the manufacture of photographic films;

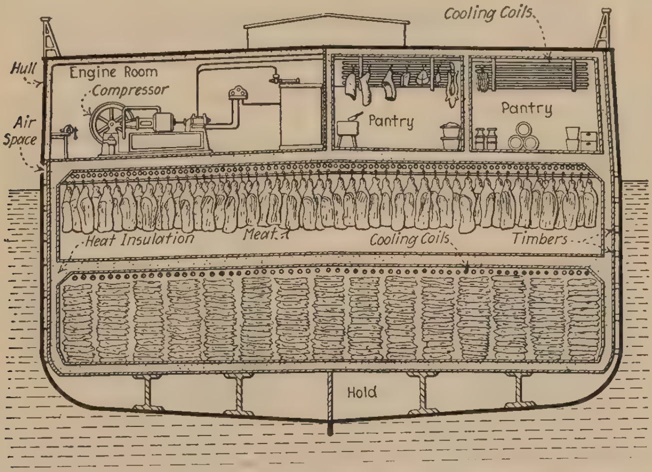


FIG. 542.—Cross-section of ship equipped with refrigeration plant for the shipment of perishable foods.

and its use in shaft sinking in freezing a ring of quicksand so that an excavation can be made through the material. These examples are given to show the broad application of refrigeration and how its development has influenced many industries.

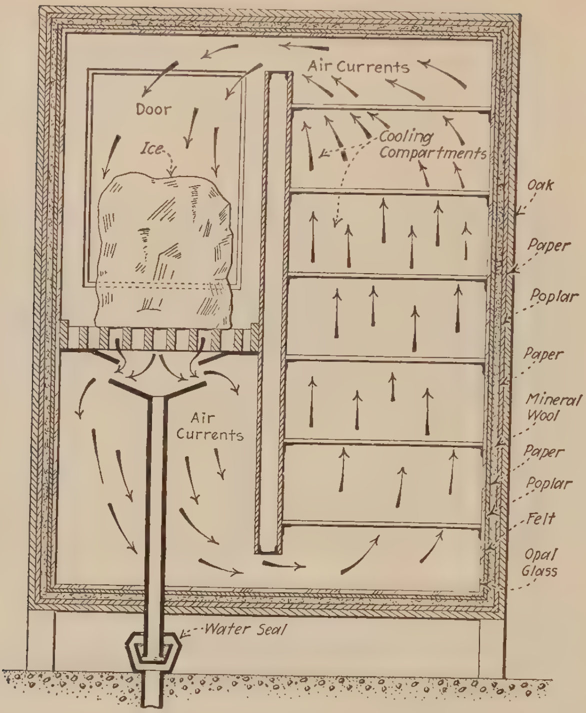


Fig. 543.—Domestic refrigerator.

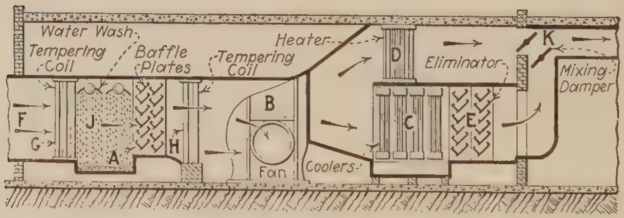


Fig. 544.—Air conditioning and cooling equipment for an auditorium. Air enters at *F*, and, in cold weather, is warmed by coils, *G* and *H*. Otherwise it only passes through the washer, *J*, and the separator baffle plates, *A*, in which the excess moisture is removed. The air then enters the fan, *B*, and after leaving it, the air may follow one of two paths. It may either flow through the heater, *D*, which serves to heat the air, or it can flow through the cooling coils, *C*, which cool the air and condense the moisture in it and the eliminator or separator *E*, which removes the moisture. The mixing dampers, *K*, are used to get a proper temperature of discharged air.

618. All Refrigeration Processes Are But The Reverse Of Heating Processes And The Fundamental Requirements Of Both Are The Same.—Most of the fundamental principles given in Div. 17 relating to heating and ventilation apply, in general, to refrigeration. In Div. 17 on Building Warming it was shown that the chief requirements for a good heating system are: (1) *A well-insulated compartment or room; the better the insulation the smaller the heat-generating unit required.* (2) *A furnace at a higher temperature than the room and large enough to produce or generate sufficient heat to compensate for the heat losses by conduction and infiltration.* (3) *A carrier or medium that will convey the heat from the furnace to the room to be heated.* (4) *Sufficient heating surface so that the heat generated in the furnace can be transferred at the desired rate to the heating medium.* The similar chief requirements for a good refrigeration system are: (1) *A well-insulated compartment or room; the better the insulation the smaller the heat-absorption unit required.* (2) *A substance that will absorb sufficient heat at or below the required temperature in the room to compensate for the conduction and infiltration losses.* (3) *A carrier that will convey the heat from the room to the cooling substance or medium.* (4) *Enough cooling surface so that the heat in the room can be transferred at the desired rate to the refrigerant.* Further similarity and also the disparity of the heating and refrigerating processes will be discussed at various other places in this division.

Note.—By "Refrigerant" Is Meant the working fluid that does the original cooling at the low temperature—at a temperature lower than that of the substance to be cooled. Where ice is used, the ice is called the refrigerant, while in vapor and gas processes the vapor or gas is called the refrigerant; although the condenser cooling water absorbs heat from the vapor or gas, it is not called the refrigerant because it absorbs heat at a higher temperature than that of the cooled substance.

Note.—A Refrigerator is a box or room for keeping food or other articles cool. It includes a refrigerated space and the surrounding insulation walls.

619. To Insure Maximum Economy, A Refrigerated Space Should Be Surrounded By Good Heat Insulation; see Figs. 542, 543 and other illustrations in this division. It has been shown in Sec. 111 that heat will pass through—or be conducted by—any substance, but that some substances are better heat insulators—poorer conductors of heat—than other substances. If these insulators, some of which are relatively cheap, are placed around a refrigerated space, less heat will leak into the refrigerated space. Consequently, the amount of heat that must be absorbed from that space will be greatly decreased. In building warming, heat insulation likewise reduces the amount of heat (Sec. 566) that must be furnished to the building. But good insulation is not such an important a factor in building warming as it is in refrigeration because the cost of delivering 1 B.t.u. to a building is only about $\frac{1}{40}$ of that of abstracting 1 B.t.u. from a room or building. It is because of the high cost of absorbing heat that a considerable investment for good heat insulation is justified and economical

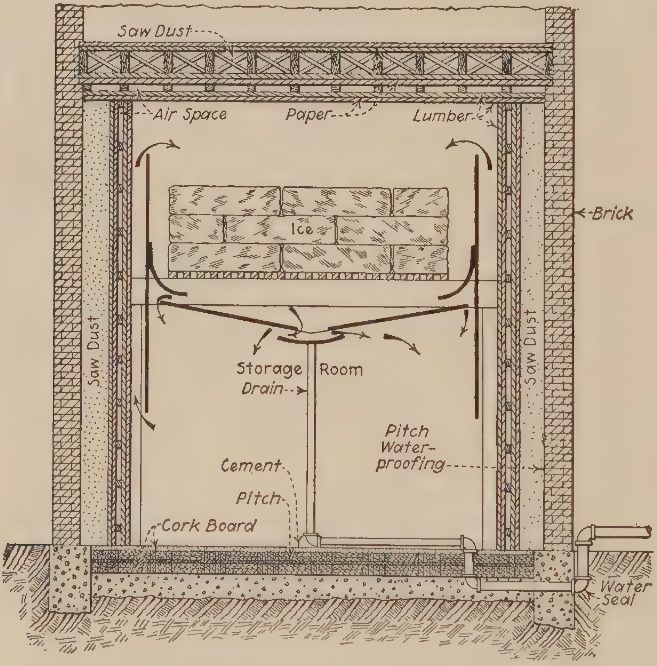


Fig. 545.—Jackson system of cold storage.

in refrigeration processes. Even small family "ice boxes" (Fig. 543) are well insulated.

NOTE.—VARIOUS MATERIALS HAVE BEEN USED IN REFRIGERATION FOR HEAT INSULATORS but the following are the more important ones used in cold-storage-room walls. cork, wood, paper, mineral wool, shavings, wood saw-dust, and air spaces. The cross-section of a cold-storage-room wall is shown in Fig. 545. If the temperatures on the two sides of an insulated wall are known, the rate at which heat that will pass through the wall may be calculated by the method given in Divs. 5 and 17 and the values given in Tables 125 and 567.

620. The Many Methods By Which Refrigeration Can Be Accomplished May Be Divided Into Two Classes: (1) *Natural refrigeration processes.* (2) *Mechanical refrigeration processes.* Natural refrigeration processes are those in which a body is cooled without any mechanical work being done during the process. In these, the cooling is accomplished by evaporating or melting the refrigerant; thereby absorbing an amount of heat, equal to the latent heat of evaporation or melting of the refrigerant (Secs. 289 and 328), from the body to be cooled. Mechanical refrigeration processes are those processes in which mechanical work is done in cooling a body. These processes also usually cool by absorbing the latent heat of evaporation of the refrigerant (which is used over and over again) but work is done, as will be explained, in bringing the refrigerant back to its original state. In some of these mechanical processes, as for example in those employing the air-machine (Sec. 644), cooling is not accomplished by the absorption of the latent heat of a vapor but by the absorption of the sensible heat of a gas.

NOTE.—THESE TWO CLASSES OF REFRIGERATION PROCESSES MAY BE COMBINED as when manufactured or artificial ice is used in a refrigerator. In this case, a mechanical refrigeration process is used to produce the ice, while a natural refrigeration process is used when the substances in the refrigerator are cooled by the ice.

621. There Are Three Natural Refrigeration Processes: (1) *Cooling by surface evaporation;* (2) *Cooling by the melting of solids;* (3) *Cooling by freezing mixtures.*

622. Natural Refrigeration By Surface Evaporation is one of the simplest methods of cooling a substance (Sec. 300).

This method has been used for ages and is still used. In this method the surface of the vessel containing the material to be maintained cool, is kept wet with a thin film of water. If drinking water is to be kept cool, a porous vessel may be used through which the water seeps slowly. Then the water that comes through to the outer surface of the vessel evaporates, and absorbs its latent heat of vaporization from the vessel and the drinking water within it. In this way the surface of the vessel and the drinking water within are kept cool. Other substances may be cooled in the same manner by supporting them within the jar above the water. Thus the cooling of the water cools the other substances. In a similar manner, the sprinkling of hot pavements in the summer affords a cool feeling of relief—because of the surface evaporation of the water on the pavement. There are many other simple examples of cooling by surface evaporation, for which see Sec. 300. This process, however, has never been utilized on a large scale except in power-plant cooling towers and ponds, Sec. 293.

Note.—When Water Evaporates From The Surface Of A Vessel, the evaporating water does not boil but evaporates slowly at the wet-bulb temperature. The latent heat of vaporization which is absorbed will then be that which corresponds to the wet-bulb temperature. See Secs. 296 and 313 for definitions of "boil" and "evaporate."

Note.—The Minimum Temperature Obtainable By Surface Evaporation Is The Wet-bulb-thermometer Temperature, Sec. 334. Thus, very low temperatures cannot, under ordinary conditions, be obtained by this method. Also since the wet-bulb-thermometer temperature depends on the humidity (Sec. 333) of the atmosphere, the lowest temperature obtainable will vary with the humidity.

Example.—It is desired to cool (by evaporation) water which is at a temperature of 60° F. by permitting it to trickle through atmospheric air. If the entering atmospheric air is at 70° F. and has a relative humidity of 40 per cent. and the leaving air is at 60° F. and 100 per cent. relative humidity, how much heat was absorbed by one pound of dry air and its vapor content?

Solution.—From the psychrometric chart, Fig. 323, Div. 10, the point of intersection between the 70° F. dry-bulb temperature line and the 40 per cent. relative humidity line, shows that the wet-bulb temperature under the initial given conditions is 56° F. It has been found by experiment that the heat content for initial conditions—no matter what they are—is the same as that for the wet-bulb temperature for the initial conditions. At the wet-bulb temperature the air is dry and saturated. Thus, the heat content for the air at initial conditions is the same as the heat content for dry and saturated air at the wet-bulb temperature. This heat content can be found from the psychrometric chart by following up the vertical dry temperature line, 56° F., until curve D is reached, then following along the horizontal line to the left and reading the heat content from the scale D. This value is found to be 23.5 B.t.u. In this example the wet-bulb temperature of the leaving air would—since the humidity is 100 per cent.—be the same as the dry-bulb temperature, or 60° F. The heat content of the leaving air can be obtained in a manner similar to that used for the initial condition. That is, it can be obtained by determining the heat content of dry and saturated air for the wet-bulb temperature, 60° F. This is found to be 26.0 B.t.u. Thus, *the heat which the air absorbed* = 26.0 − 23.5 or 2.5 *B.t.u. per lb.*

623. Natural Refrigeration By The Melting Of Solids Is The Most Common Of All Refrigerating Processes.—The solid which is generally used is *ice*. Refrigeration by the melting of ice was more extensively employed in the past—before other, better methods were developed—than it is at present. The melting of ice is still, however, the best method of cooling for small refrigerators, such as the family refrigerator (Fig. 543) in which food stuffs are kept cool during the hot summer months. The principle underlying the process of refrigeration by the melting of ice—or any solid—is simply the fact that when a solid melts it absorbs its latent heat fusion (Sec. 289) from the surrounding air or objects. The latent heat of fusion of ice is 144 B.t.u. per lb. This amount of heat is, necessarily, absorbed from the surrounding substances whenever 1 lb. of ice melts (see Sec. 290). Since pure ice melts, under atmospheric pressure, at 32° F., the *minimum temperature* obtainable under ordinary conditions by melting ice is 32° F.

Note.—Ice Is The Most Convenient—And In Fact The Only Usable—Solid For This Process Of Refrigeration.—While all solids, such as iron and lead, absorb heat when they are melted, still they cannot be used for cooling objects below normal atmospheric temperatures, because their melting points are too high—above average atmospheric temperature. Other solidified liquids could theoretically be used for refrigeration by allowing them to melt, but their melting points are so low (below atmospheric temperature) that they would melt during transportation, making them difficult to handle. Besides they would be expensive. In addition, the liquid resulting from the melting, being more scarce, would have to be saved. Until recent years, natural ice was widely harvested in winter and stored for use in hot weather. Now, however, artificial ice (Sec. 647) is largely eliminating the necessity of natural-ice storage.

Example.—An ice-box with an exposure or exposed surface of 40 sq. ft. has a leakage of 0.8 B.t.u. per sq. ft. per hr. The heat that must be absorbed from warm food which is placed in the box averages 60 B.t.u. per hour. What will be the amount of ice melted in the box in 24 hr.? Solution.—*Heat absorbed by ice in 24 hr.* = $(40 \times 0.8 + 60) \times 24 =$ 2,208 *B.t.u. Ice required* = $2{,}208 \div 144 = 15.3$ *lb. per 24 hr.*, when latent heat of fusion of ice is 144 B.t.u. per lb.

624. Air Is Generally The Heat Carrier In The Refrigeration Processes In Which The Melting Of Ice Produces The Cooling Effect.—In the family refrigerator or "ice box" (Fig. 543) and in the cold-storage room, cooled with ice (Fig. 546), the process is essentially the same. The ice is placed in a bunker at the top of the storage space. This bunker may either be in the form of a tank having one side removed (Fig. 546) or it may be in the form of a tank having three holes in its bottom, one at the center and one near each side (Fig. 545). Ample spaces are provided between the sides of the bunker and the sides of the room to permit the air to circulate freely. The floor of the bunker is made watertight and it is heat-insulated from the storage space. The air in the vicinity of the ice is thereby cooled and creates a natural circulation of air, over the ice, through the ducts, and across the cold-storage space. The natural circulation of air in a cold storage plant is similar to and is governed by the same general laws as the natural draft in a chimney; Sec. 256. The flow of air takes place because of the difference in pressures due to the difference in temperatures (densities) of the air along its path.

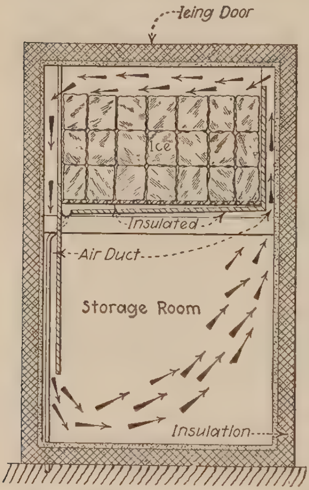


Fig. 546.—Ordinary system of cold storage.

To insure maximum circulation, the temperature difference must be as large as possible. This is accomplished by insulating the ducts and making them as long as possible. The ratio of the height of the cooler to the width between hot and cold air ducts should be kept as great as is feasible.

Note.—The Shape Of The Bunker Greatly Affects The Air Circulation.—If the bunker were of the form of a tank without one side removed or were without holes in its bottom, the cold heavy air would sink to the bottom of the bunker and remain there; then there would be no circulation. If the bunker had both sides removed, the tendency would be for the air to flow off the ice in both directions, thereby giving rise to conflicting currents of air. The bunker floor should be insulated to prevent cooling of the air next to the bunker floor which would hinder circulation. Note also the construction of the ice-cooled railway car of Fig. 541.

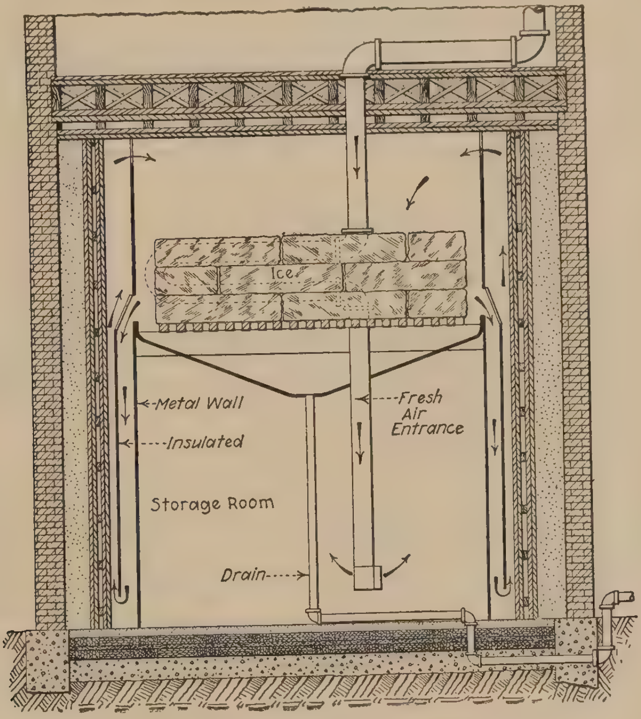


Fig. 547.—Dexter system of cold storage.

NOTE.—IN SOME ARRANGEMENTS THE AIR OF THE COOLER DOES NOT COME IN CONTACT WITH THE MELTING ICE. In this case, as shown in Fig. 547, the air is chilled by contact with the metallic walls which in turn are cooled by cold air passing over them.

625. The Refrigeration Processes In Which Air Is The Heat Carrier Are Similar To The Process Of Heating By Means Of Hot Air.—In both cases, air is the heat carrier in which the heat is temporarily stored for transportation. In the warm-air heating system (Fig. 531), air is heated in the furnace or bunker coil and then passes through ducts by natural or forced draft to the registers in the rooms. In the rooms, as the hot air comes in contact with the cold windows, walls, etc., it gives up some of its heat. The now chilled air, because of its greater density, flows by gravity back to the furnace or the heater. This heating process is very similar to the refrigerating process described in the preceding section. Just as the success of the heating process depends on: (1) *sufficient heating surface in the furnace*, (2) *sufficient coal to generate the amount of heat to be given to the rooms*, and (3) *proper air ducts to insure unrestricted flow of air*, so likewise the success of the refrigerating process depends on: (1) *sufficient cooling surface*, (2) *sufficient amount of refrigerant to absorb the heat which must be taken from the room*, and (3) *proper ducts to permit unrestricted air circulation.*

626. Temperatures Lower Than 32° F. Can Be Obtained With "Freezing Mixtures;" see also Sec. 287. Freezing mixtures, sometimes called *cryogens*, are solutions which produce a drop in temperature by *certain endothermic* reactions. An endothermic reaction (Sec. 157) is one whereby heat is absorbed. It has long been known that the addition of a foreign substance to a liquid often lowers its freezing point. This addition of a foreign substance to a liquid produces a freezing mixture. One of the most common examples is a mixture of salt and ice. The melting point of the ice is reduced by the salt. Consequently, a mixture of salt and ice will give a lower temperature than 32° F. (see Sec. 287). Freezing mixtures of salt and ice are commonly used in ice-cream freezers. They have also been used in some cold-storage plants as shown in Fig. 548.

EXPLANATION.—The arrangement of Fig. 548 consists, essentially, of a tank, *T*, for holding the freezing mixture, and a continuous pipe circuit, *P*, partly located in the ice compartment and partly in the cold-storage compartment, *C*. The pipe is filled with brine—a mixture of salt and water—which is the heat carrier and which conveys the abstracted heat from the cold-storage compartment to the freezing, mixture, where the heat is absorbed from the brine. There is a natural circulation of the brine in the pipe, because of the difference in density caused by the difference in temperature, similar to that of the air in Figs. 545, 546 and 547. This process has seldom been used because of expense, dirt, and icing troubles. It has all the disadvantages of the previously described processes, except that a lower temperature is obtainable.

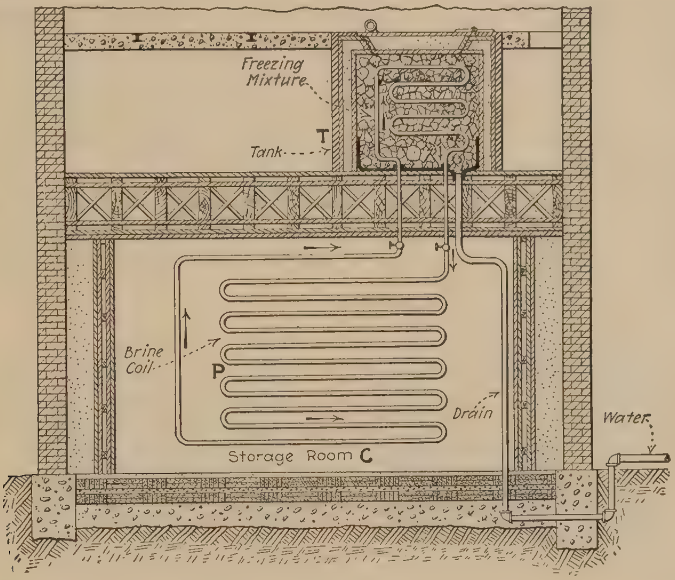


FIG. 548.—Cooper gravity brine-circulating system.

NOTE.—THIS IS AN INDIRECT SYSTEM AND IT IS SIMILAR TO THE HOT-WATER SYSTEM of building warming. The freezing mixture in Fig. 548 cools the brine which in turn cools the cold-storage room, while in the hot-water heating system the furnace heats the water which in turn heats the room. Both systems convey the heat by means of the natural circulation of a liquid. In both systems, the heat transmitting surfaces—the cooling coils of the refrigerating system, one in the freezing mixture compartment and one in the cold-storage room, and the heating surfaces of the heating system, one in the furnace and the other in the radiator—must be of the proper size and shape to insure successful operation. In the refrigeration system, the cooling coil should be placed in the warmest part of the cold-storage room which is near the doors and ceiling, instead of in the coldest part as is the radiator in the heating system.

627. Mechanical Refrigerating Processes Are Of Two Principal Types. (1) *Vapor processes.* (2) *Gas processes.* Each is further discussed hereinafter. In these processes, by utilizing machines, heat may be caused, by virtue of mechanical energy expended, to flow from a body of low temperature (the refrigerated space) to a body of higher temperature (generally the coldest available natural steam of water). Note that as stated by the Second Law Of Thermodynamics (Sec. 84) "Heat will not flow of itself from a cool to a hotter body. "A refrigerating machine" and "a refrigerating-machine cycle" are defined in Sec. 403.

NOTE.—MECHANICAL REFRIGERATION MACHINES ARE SOMETIMES CALLED "HEAT PUMPS" because by virtue of the mechanical energy—supplied by some outside force—which is expended in them, they *force* heat to flow from a cool to a hotter body. This idea of "pumping heat" from a low to a high level (temperature) may prove valuable.

628. Vapor Refrigerating Processes are those wherein the working substance (refrigerant) passes alternately through its liquid and vapor states. In these processes, a substance is used for the refrigerant which, when in its liquid state, will boil (Fig. 549) readily at a temperature below that desired in the space to be cooled. In thus boiling and changing to its vapor condition, the substance absorbs its latent heat of vaporization from the space which is to be cooled. So that the substance can be again used, it must be restored to its initial or liquid state by the expenditure of mechanical work on and by cooling it. This process is further explained hereinafter. The vapor refrigerating machine cycle is explained in Sec. 433.

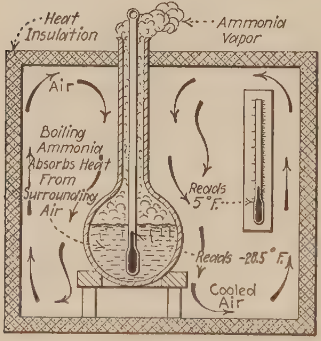
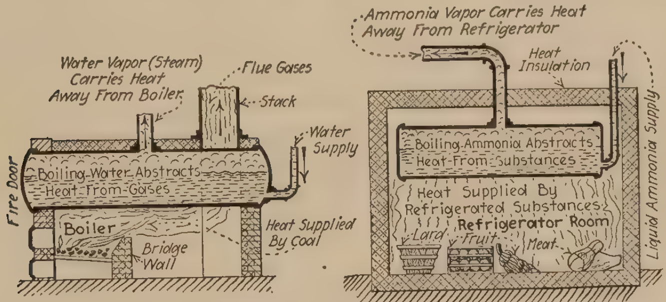


FIG. 549.—The elements of a direct-expansion ammonia-vapor refrigerating system.

629. Gas Refrigerating Processes are those wherein the working substance or refrigerant (usually air) remains in the gaseous state throughout the entire cycle of changes which it is made to undergo. In these processes of refrigeration, the gas is first cooled below the temperature desired in the space which is to be cooled. The gas is thus initially cooled by allowing it to do work by expansion. The now cool gas is then permitted to absorb heat from the refrigerated space. To restore the heated gas to its original cool condition, mechanical work must be done on it, as is explained in Sec. 644.

630. The Vapor Refrigerating Apparatus Is Similar To A Steam Boiler (see Fig. 550).—Both operate on the principle that heat is required to vaporize liquids. A simple arrangement for the generation of steam is to allow water to flow through a coil located in a furnace. As the water is at a lower temperature than the furnace gases, it will absorb heat therefrom and its temperature will increase. Also, since water boils at a lower temperature than that of the furnace gases, it will, when it reaches its boiling temperature, vaporize into steam. To effect this vaporization, heat is absorbed by the water from the furnace gases. Each pound of steam will abstract from the furnace an amount of heat equal to its latent heat of vaporization at the boiling pressure and in addition the heat required to raise the temperature of the water to that at which it boils (see Sec. 365). The process would (if fuel were not continually added to the furnace) continue until the


Water Vapor (Steam) Carries Heat Away From Boiler
Flue Gases
Stack
Water Supply
Fire Door
Boiling Water Abstracts Heat From Gases
Boiler
Bridge Wall
Heat Supplied By Coal
Ammonia Vapor Carries Heat Away From Refrigerator
Heat Insulation
Liquid Ammonia Supply
Boiling Ammonia Abstracts Heat From Substances
Heat Supplied By Refrigerated Substances
Refrigerator Room
Lard
Fruit
Meat

I-Steam Boiler-Simple Type

II-Ammonia Boiler-Simple Type

Fig. 550.—Showing similarity between a steam boiler and an ammonia expansion coil which is in reality an "ammonia boiler."

furnace temperature was reduced to that of the boiling water and steam.

631. While The Above Process Is Called A Heating Process, Because Its Object Is The Vaporization Of The Water, It Could Be Called A Refrigeration Process If The Object Were To Cool The Furnace Gases.—In practical refrigeration, temperatures below that of the atmosphere are desired. As water under the normal pressure—atmospheric and greater—boils at a higher temperature than that of the atmosphere and as heat will not of itself flow from a lower to a higher temperature, the above process must be modified if it is to be employed in practical refrigeration—to cool objects below atmospheric temperatures. A suitable modification can be effected in one of the following two ways: (1) *By using a liquid that will boil under normal pressures at a temperature below that of the atmosphere*, as is explained in the sections which immediately follow. (2) *By reducing the pressure on the water and thereby lowering its boiling temperature*, as is explained in Sec. 640.

632. Substances Which, In The Liquid State, Have A Low Boiling Temperature Under Ordinary Pressures Are Generally Used As The Refrigerant In Vapor Refrigeration Processes. A substance which, in the liquid state, has a comparatively low boiling temperature (such as ammonia which boils under atmospheric pressure at $-28.2°$ F.) will boil (Fig. 549) in an open container, that is, under atmospheric pressure, at room temperatures. Since the boiling temperature of a liquid increases with the pressure, these liquids can be preserved and shipped in the liquid state by keeping them in steel drums or tanks under pressures high enough to prevent vaporization at ordinary temperatures. When a cooling effect is desired, such a liquid can be allowed to escape from the tank, under high pressure, into the low atmospheric pressure. Under atmospheric pressure, the liquid will boil and vaporize and absorb its latent heat of vaporization from its surroundings.

Explanation.—Suppose that in the arrangement shown in Fig. 551, such a liquefied substance, for example ammonia, is allowed to flow from the tank where it is kept under high pressure, through the regulating valve *V*. It will then enter the expansion coil, *C*, which being open to the atmosphere, will then have in it a pressure equal to or somewhat greater than atmospheric. Since ammonia under atmospheric pressure boils at $-28.2°$ F., it will boil in coils, *C*, and absorb heat from the room *R*, and vaporize into ammonia vapor. Each pound of liquid which vaporizes will absorb from the room an amount of heat equal to the difference between the total heat of the vapor at the boiling pressure and the total heat of the liquid at its temperature in the tank.

If sufficient ammonia were allowed to flow through the coil, the temperature of the room could be reduced to almost that (—28.2° F.) of the boiling ammonia. Some temperature difference would be required to cause the heat to flow to the ammonia. The *regulation valve, V*—sometimes called the *expansion valve*—is used to regulate the flow of the liquid so vaporization takes place at such a rate that the desired low temperature will be maintained in the room. After vaporization, the ammonia vapor will exhaust into the atmosphere at *A* and be lost. Since ammonia and the other liquids which have low boiling points are very expensive, such a process would be too costly to be used commercially. If the vapor process is to be utilized commercially, some method must be devised whereby the vapor can be used repeatedly, without discarding it into the atmosphere. This can be accomplished only by restoring the vapor to its original condition—that is liquefying it—by some means of extracting heat from it; see following sections.

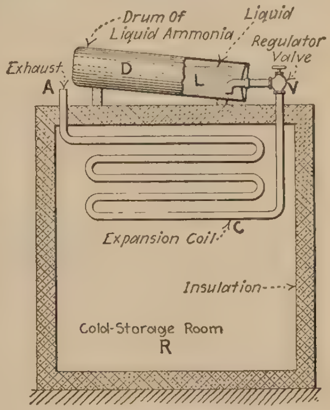


FIG. 551.—Simple form of vapor refrigeration plant.

EXAMPLE.—Assuming that 7,500 B.t.u. must be absorbed from a room per hour, how many pounds of anhydrous ammonia at a temperature of 95° F. must be vaporized, at a pressure of 23.3 lb. per sq. in. abs., each hour to abstract this 7,500 B.t.u. per hr? SOLUTION.—The heat absorbed by 1 lb. of anhydrous ammonia is equal to the difference between the total heat of the saturated vapor at 23.3 lb. per sq. in. abs. and the heat of the liquid at 95° F. From Table 400, Div. 11, the total heat of saturated ammonia vapor at 23.3 lb. per sq. in. abs. is found to be 535.7 B.t.u. per lb. The heat of the liquid ammonia at 95° F. is also found to be 71.3 B.t.u. per lb. Then, *the heat absorbed by 1 lb. of ammonia* = 535.7 − 71.3 = 464.4 *B.t.u.* Hence, *the amount of ammonia which must be vaporized per hour* = 7,500 ÷ (*heat absorbed by 1 lb. of ammonia*) = 7,500 ÷ 464.4 = 16.15 *lb. per hr.*

NOTE.—THE SUBSTANCES PRINCIPALLY USED IN COMMERCIAL VAPOR REFRIGERATING MACHINES ARE AMMONIA, SULPHUR DIOXIDE, AND CARBON DIOXIDE (see Sec. 398). Other substances could be used but they are not as economical or as desirable. The boiling temperature of a suitable substance under normal pressures should lie within certain limits (see Fig. 552). If the boiling temperature is too low under ordinary pressure (as with liquid air, for example), excessive pressures would be necessary to preserve the liquid in the drum in the liquid state. Vapors which would require these high pressures would be difficult to liquefy and, when liquefied, would necessitate very strong storage receptacles. Other factors which determine the suitability of a liquid are its specific volume, its cost, and the effect of its fumes upon the human health. Ammonia is probably the most widely used because it in vaporizing affords reasonably low temperatures without maintaining a vacuum in the cooling coils (C, Fig. 551) and it can be restored easily to its initial condition—condensed with relatively warm water when compressed to only moderately high pressures. Sulphur dioxide condenses at even lower pressures, with relatively warm condensing water, than does ammonia but for low temperatures it must be evaporated in a partial vacuum. It is used to advantage in the tropics. Carbon dioxide is well adapted for very low-temperature refrigeration, but it must be worked at very high pressures and requires cool condensing water for high efficiency.

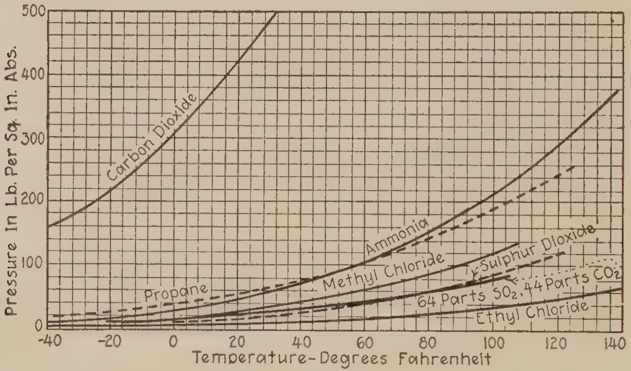


Fig. 552.—Graphs showing variation of boiling temperatures with pressures of various substances used in mechanical refrigerating processes. Note the curve for water is so close to the base line that it has been omitted, the pressure being only 3 lb. per sq. in. abs. at 141° F.

633. Before The Vaporized Liquid In A Mechanical Refrigeration Process Can Be Used Over Again (Made To Re-absorb Its Latent Heat) It Must Be Restored To Its Initial Liquid Condition. The action of the refrigerant vapor in absorbing heat (as in C, Fig. 551) is similar to the action of a sponge absorbing water. After the refrigerant (such as ammonia), has absorbed heat and vaporized it is in a position corresponding to the sponge partly filled with water. In order that the sponge be restored to its original condition, the water absorbed must be squeezed out, by a pressure of the hand. Likewise in order that the vapor be restored to its original liquid condition, the heat it has absorbed from the refrigerated objects must be driven out, or extracted in some manner.

634. This Extraction Of Heat Can Be Effected By One Of Two Processes: (1) *The compression process.* (2) *The absorption process.* In the compression process of mechanical refrigeration, the heated vapor is first compressed and then condensed by cooling it with air or water. The compressor (*R*, Fig. 553) does work on the vapor and increases the pressure upon it, thereby making it possible to liquefy it with relatively warm cooling water. The pressure thus produced must be sufficiently great that the boiling point of the substance under that pressure is greater than the temperature of the cooling water; if the pressure were lower the vapor could not be liquefied. In the absorption process of mechanical refrigeration (Sec. 637) the vapor is first absorbed by water, which will absorb 800 to 1,000 times its own volume of ammonia vapor under atmospheric pressure. The solution of ammonia is then heated, causing some of the ammonia to be vaporized at a high pressure, and the vapor is then liquefied by cooling it with water.

635. The Essential Parts Of A Vapor Compression Process Are (see Figs. 553 and 554): (1) *An expansion coil, V.* (2) *A compressor, R.* (3) A condenser, *C*, see Figs. 555, 556, 557 and 558. (4) *An expansion valve, E*, see Fig. 559. (5) *A liquid receiver, L.* (6) *A vapor refrigerant, ammonia in Fig.* 553. (7) *A cooling medium, cooling water in Fig.* 553. Thus the essential parts of a vapor compression process and their relation to each other are shown in Fig. 553. This system is the same as the elementary apparatus shown in Fig. 551 with the addition of the compressor and the condenser. The function of these two parts is, as hereinbefore explained, to restore the vapor to its initial liquid condition.

Explanation.—The path of the refrigerant, shown in Fig. 553 by the arrows, from the liquid receiver, *L*, through the expansion coils, *V*, and the operations that occur therein, are the same as those in the elementary system shown in Fig. 551. After leaving the expansion coils, the vapor, enters the compressor, C, in which it is compressed to such a pressure, that it may be liquefied with the cooling water of the temperature which

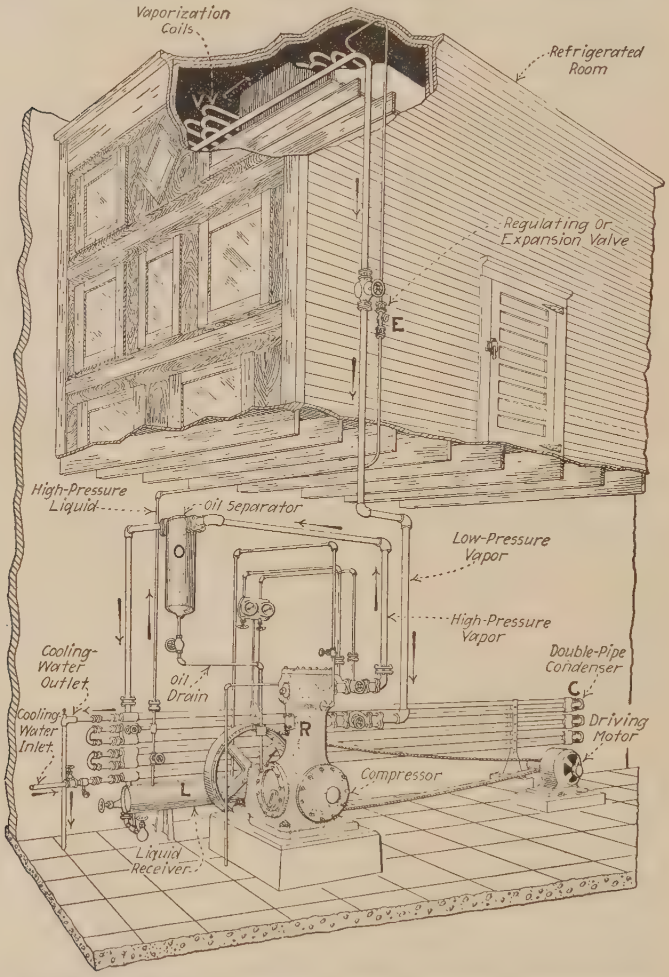


Fig. 553.—A typical small compression vapor installation. The condenser, C, called a double pipe condenser, consists of two concentric pipes. The cooling water flows through the inner pipe and the ammonia flows between the two pipes as shown in Fig. 557. (*The Vilter Manufacturing Co.*)

is available. From the compressor, the vapor passes through an oil separator, O, which separates the oil from it and then to the condenser, several types are shown Figs. 555, 556 and 558. While the separator

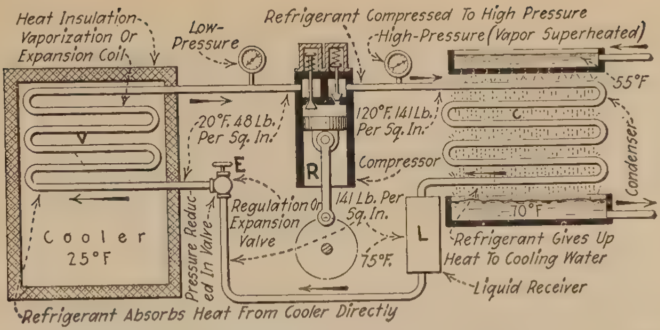

Heat Insulation
Vaporization Or Expansion Coil
Low-Pressure
Refrigerant Compressed To High Pressure
High-Pressure (Vapor Superheated)
55°F
-20°F. 48 Lb. Per Sq. In.
120°F. 141 Lb. Per Sq. In.
C
Condenser
E
R
Compressor
Regulation Or Expansion Valve
141 Lb. Per Sq. In.
70°F
L
Cooler 25°F
Pressure Reduced In Valve
75°F.
Refrigerant Gives Up Heat To Cooling Water
Liquid Receiver
Refrigerant Absorbs Heat From Cooler Directly

FIG. 554.—Circuit of direct-expansion compression refrigeration system. See Fig. 569 in regard to temperatures and pressures.

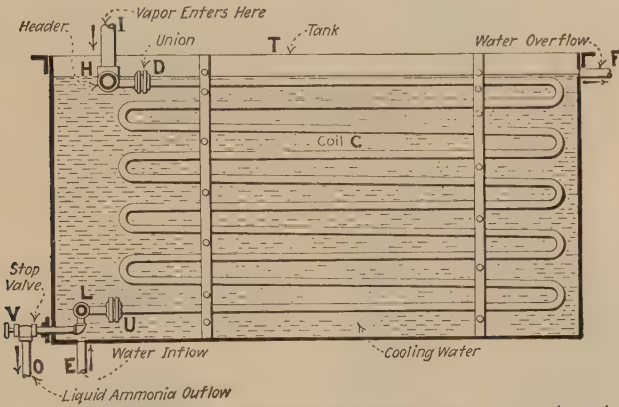


FIG. 555.—Cross-section of a submerged condenser. The vapor enters at *I*, passes through the header, *H*, and the coil, *C*, where it is liquefied. It then flows through the lower header, *L*, the stop valve, *V*, and out through, *O*. The cooling water enters at *E* and overflows at *F*. The same apparatus may be used as a brine cooler, if desired.

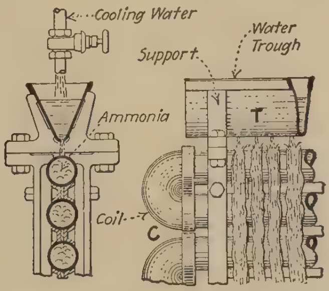


FIG. 556.—Section of atmospheric condenser. The ammonia vapor to be condensed flows through the coil, *C*, either upward from the bottom to the top or downward from the top to the bottom. The cool water flows from the trough, *T*, through small holes in its bottom, over the coils, *C* thereby condensing the ammonia vapor. The falling water is caught in pans at the bottom of coil.

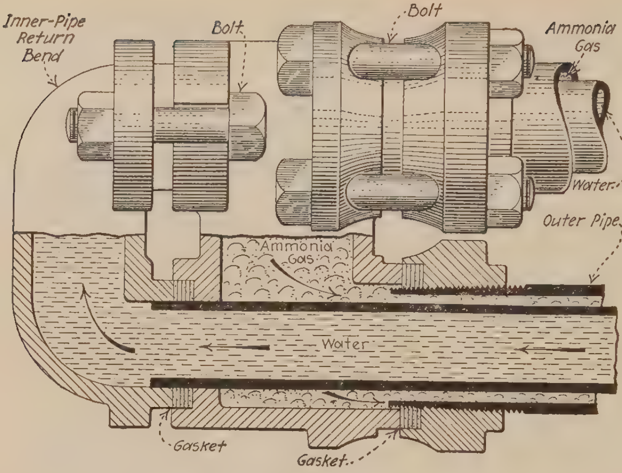


Fig. 557.—Detail of double-pipe condenser.

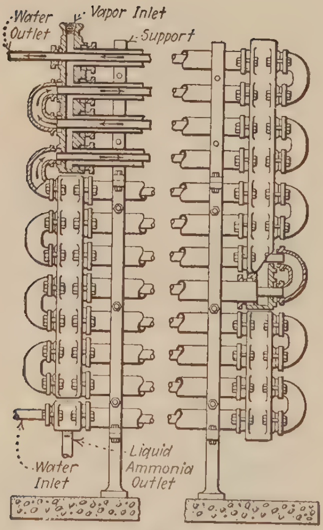


Fig. 558.—A double-pipe condenser or brine cooler. Arrows show direction of flow of water and of ammonia when used as a condenser. See Fig. 557 for detail.

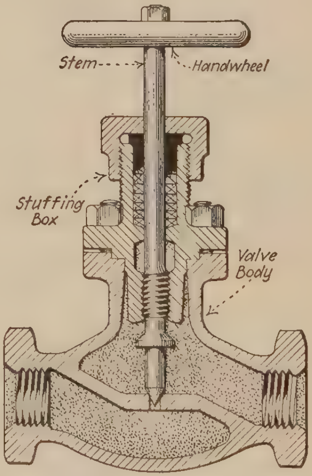


Fig. 559.—Rising-stem-type ammonia expansion valve. (*Crane Co.*)

is not essential, it is desirable as it prevents oil (which is used in lubricating the compressor cylinder) from getting in the condenser coils and increasing the heat transmission resistance thereof. In flowing through the condenser the vapor, being under high pressure, is condensed to the liquid state by the cooling water. The now liquefied vapor then flows into the liquid receiver, L, completing its cycle. The pressure upon the liquid in the receiver is, neglecting the drop through the pipes, the same as that on the vapor in the condenser.

636. The Function Of The Compressor In The Vapor Compression System (R, Fig. 553 and Figs. 560 and 561) is to remove the vapor as promptly as it is formed and then compress it to a pressure sufficiently high so that the vapor can be condensed by the cooling water or air at hand. As stated in Sec. 426 a compressor is an essential part of every refrigerating machine. To condense a vapor, heat must be extracted from it. Since heat of itself always flows from a higher to a lower temperature, this heat can be extracted only by allowing it to flow from the vapor to a colder substance. In the refrigeration process, the boiling (or liquefaction) temperature of the vapor at the pressure in the expansion coil is below that of any available cooling medium. Hence, work must be done upon the vapor and its temperature of boiling increased so that it can be condensed by the available cooling medium. The compressor may be driven by a steam engine, electri motor or a water wheel—whichever is the most economical.

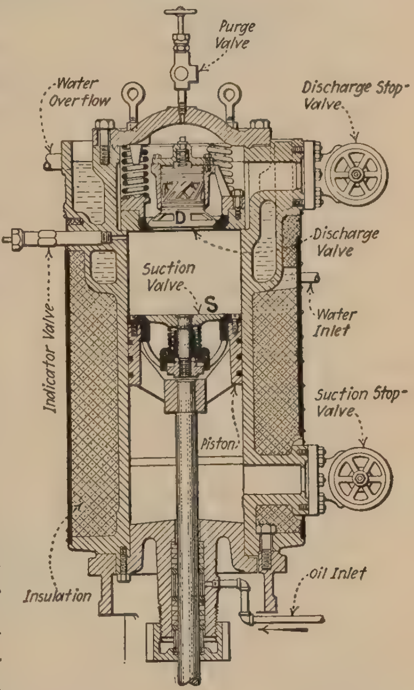


Fig. 560.—Section of *York* ammonia-compressor cylinder. The suction valve, S, is practically balanced, the spring tending to hold it open and the dash pot tending to close the valve.

EXPLANATION.—Suppose it is desired to cool a room with a vapor refrigeration system to 10° F., then the ammonia must be allowed to boil (vaporize) at some temperature below this (a temperature difference or thermal pressure is necessary to effect a heat flow, Sec. 84), such as 0° F. Now the coldest available cooling medium, is say a stream of water at 60° F. It is evident that this water will not absorb heat from the vapor unless the temperature of the water is less than that of the vapor. Now, by means of a compressor, work may be done on the vapor and the temperature and pressure of the vapor may be thereby increased. If the compression of the vapor is carried sufficiently far—to about 130 lb. per sq. in. abs. for the ammonia of this example—the vapor will then be in such a condition that it can be condensed by the available cooling

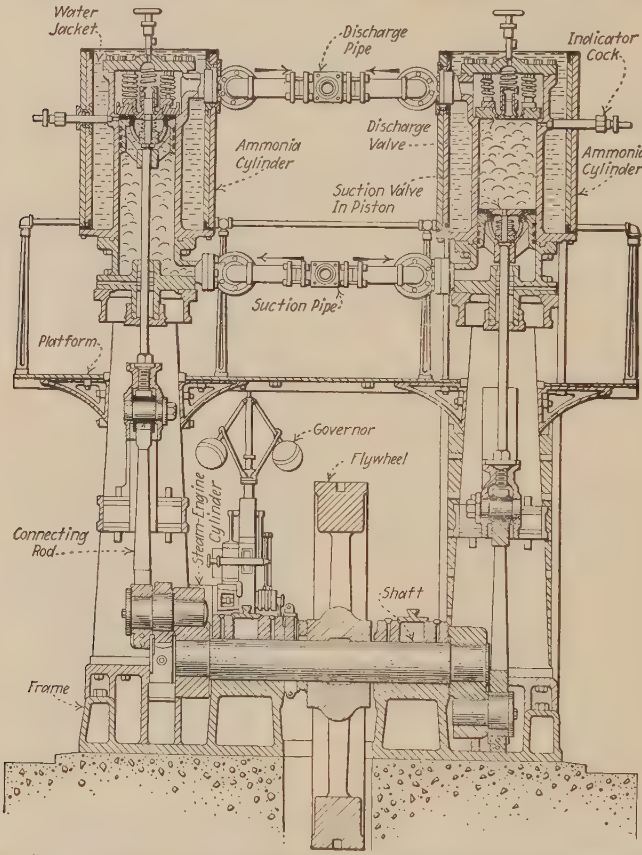


FIG. 561.—Vertical, double-cylinder steam-engine-driven ammonia compressor.

water. For, at 130 lb. per sq. in. abs. the boiling (condensing) point of ammonia is about 70° F. Thus the compressed ammonia can, by water at 60° F., easily be cooled (to 70° F.) and condensed. The condensed ammonia may now be permitted to flow to the receiver where the pressure would, neglecting losses, also be 130 lb. per sq. in. abs.

Note.—No Compressor Would Be Needed If the cooling water were colder than the vapor refrigerant coming from the expansion coil. The vapor could then be cooled directly by the water, as in steam power and steam-heating plants. However, in such a case, the cold water could be used directly as the cooling agent and no vapor refrigerant would be necessary.

637. The Absorption Vapor Process Differs From The Compression Vapor Process only in the manner of restoring the vapor to its initial liquid condition. In the compression process the pressure on the vapor and also its temperature are increased by means of a compressor. In the absorption process this pressure increase is accomplished by allowing the ammonia vapor to be absorbed by water and then driving the ammonia vapor from the water at the required pressure by partial distillation.

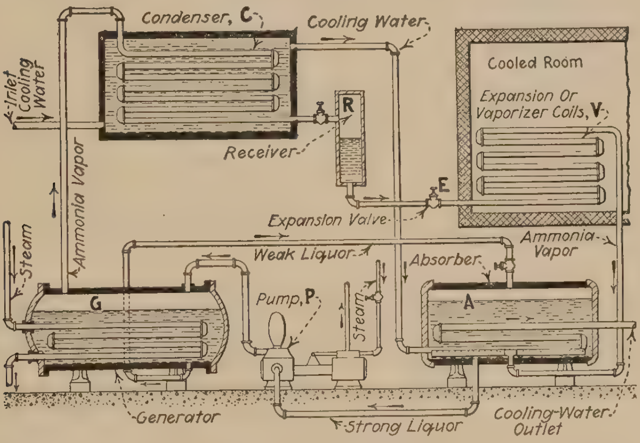


Fig. 562.—An elementary ammonia absorption refrigerating machine.

Explanation.—From the diagram of an elementary absorption process, Fig. 562, it can be seen that the process is the same as the compression process with the exception that the compressor is replaced by an absorber, *A*, ammonia pump, *P*, and a generator, *G*. Since the compression system has been described in detail it will be necessary to trace the working medium (ammonia) through only that part of the cycle between the expansion coils and the condenser. The cold ammonia vapor leaving the expansion coils, *V*, enters the absorber, *A*, which contains a relatively cold weak ammonia solution, called weak aqua ammonia. Since cold water has a great affinity for ammonia vapor, the ammonia vapor is absorbed and a strong aqua ammonia (solution) results. Heat is generated in this process of solution and must be removed by cooling water to prevent high temperatures. High temperatures hinder the absorption process, as the power of the water to absorb ammonia vapor decreases as the temperature increases.

The resulting strong aqua ammonia is pumped by an ammonia pump, *P*, to the generator or *still*, *G*. The liquid and vapor in *G* are at a relatively high pressure, hence *P* does mechanical work to pump the liquid into it. Here the solution is heated by a series of steam coils with either high- or low-pressure steam. Since the amount of ammonia that the water can hold decreases as the temperature and corresponding pressure are increased, some of the ammonia is vaporized in *G* during this heating process. This ammonia vapor must be generated at such a rate that the pressure in the condenser, *C*, will be sufficiently high to insure that the vapor will be liquefied by the cooling water which is available. The remaining weak aqua is returned to the absorber. In the commercial process a number of refinements are added to this elementary process for increasing its economy. Energy is added to the refrigerant by *P* and by the heat supplied in *G*. These energy additions provide the "heat pump" (Sec. 627).

638. A Commercial Vapor-absorption Refrigerating Installation is diagrammatically shown in Fig. 563. The apparatus is essentially the same as that of Fig. 562 with the addition of three elements: a *rectifier*, *R*, a *weak-liquid cooler*, *W*, and an *exchanger*, *E*, (sometimes called *interchanger*). These pieces of apparatus are added to conserve heat. Each interchanges heat between a hot substance which is to be cooled and a cold substance which is either to be heated or rejected from the system. The additional apparatus performs a two-fold function: (1) It decreases the amount of heat that must be furnished by the steam coils of the generator. (2) It decreases the quantity of heat that must be carried away by the cooling water.

Explanation.—In Fig. 562, the weak liquid leaves *G* at high temperature and enters *A* where its temperature should be low, and the strong liquid leaves *A* at low temperature and enters *G* where its temperature should be high. Evidently, the steam coil in *G* must supply much heat and the coil in *A* must extract much heat. It would seem desirable to utilize the cold liquid passing from A to G for cooling the hot liquid passing from G to A meanwhile heating the liquid which does the cooling. This is exactly what is accomplished by the exchanger, E, Fig. 563. It is simply a double-tube coil (Fig. 557) through which the strong and weak liquids pass in opposite directions and interchange heat. Because of the counter currents, a very effective heating and cooling is accomplished.

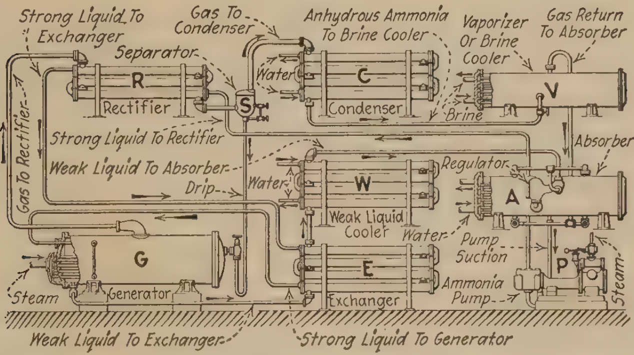


Fig. 563.—Diagram of absorption refrigerating machine. This is an indirect system, the expansion coil being located in the brine cooler, cools the brine which is circulated through coils in the room to be cooled. (*Henry Vogt Machine Co.*)

In Fig. 562, the vapor leaving G will, because of the fractional distillation process (Sec. 346), be a mixture of ammonia and water vapors. If the water vapor were not separated from the ammonia vapor, the water vapor would enter the vaporizer or refrigerating coils and at the low temperature of these coils it would freeze and clog the coils. To obviate this trouble, the cold strong liquid from the absorber is in Fig. 563 passed through the rectifier, R, on its way to the exchanger, E. The rectifier, R, is essentially a small surface condenser (Sec. 514). It cools the ammonia and water vapors which pass through it on their way to the condenser, C, and serves to condense nearly all of the water vapor. This vapor is condensed as a strong solution of ammonia, is separated from the remaining vapors by the separator, S, and flows, by gravity, to the generator. Thus the rectifier aids the condenser in its duties of cooling the vapor and simultaneously aids the exchanger in heating the cold strong liquor.

Now, because the cold strong liquor is heated somewhat by the vapors in the rectifier, it is not capable of extracting as much heat in E from the hot weak liquor as would be desirable. Furthermore, since the vapors must be cooled in C to quite a low temperature, the cooling water cannot be heated through a very great temperature range in passing through C. The temperature of the water leaving C is sufficiently low that it may be used to absorb heat from A. In A, the water temperature is again only slightly increased—the water leaving *A* at a lower temperature than that of the liquid in *A*. Hence, this water is still colder than the weak liquor leaving *E* and may be used to advantage in cooling the weak liquor before it is permitted to enter *A*. This last effect is that accomplished by the weak-liquor cooler, *W*, Fig. 563.

Sometimes a piece of apparatus which is not shown in Fig. 563 is also used. It is called an *analyzer*. An analyzer is simply an arrangement, usually built on top of the generator, whereby the strong liquid which comes from the exchanger is made to fall, in a spray or sheet, through the ascending vapors from the generator. It serves to cool the ascending vapors somewhat and perhaps to hasten the release of ammonia vapor from the incoming strong liquid. Thus, it also serves to conserve heat energy.

639. The Relative Merits Of The Absorption And Compression Processes may be summarized as follows: The absorption process is the more economical where exhaust steam is available, where low temperatures (below 0° F.) and small units (up to about 225 tons) are required, but for all other conditions the compression process is the more economical. In an absorption system the use of high-pressure steam in the generator coils is ordinarily uneconomical because the same result can, generally, be obtained much more economically by the use of low-pressure (exhaust) steam, or by the use of a steam-driven compressor (compression method). Likewise, if only enough exhaust steam is available for the necessary building heating or other purposes about the plant, the compression method is the more economical. Combined plants have been installed in which the exhaust steam from steam-driven compressors is used to operate the absorption apparatus. The absorption process is well adapted for small units when low-temperature (below 0° F.) refrigeration is desired as it can provide low temperatures with almost the same power consumption as it can high temperatures. The compression process, however, gives maximum economy with high suction pressures (temperatures). The reason for this is that at low pressures, the specific volume of vapor becomes very great and for handling large volumes of vapor the compressor cylinders must be correspondingly large; thus, the compressor consumes much mechanical energy. If an ordinary compressor is used its capacity is greatly decreased. But in the larger units (above 225 tons), the compression system becomes more efficient because of the greater efficiency of the larger steam engine. An absorption machine of a capacity of 50 to 100 tons, operating under best conditions, with a temperature in the refrigerator of not more than 0° F. gives an economy equal to that of a compression machine also operating under favorable conditions.

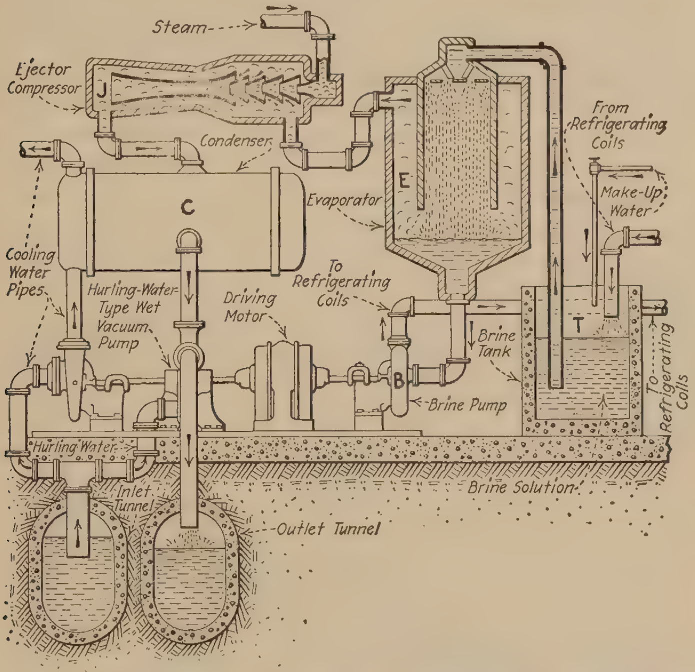


Fig. 564.—Westinghouse-Leblanc water-vapor refrigerating machine. The warm brine is contained in the brine tank, *T*. Atmospheric pressure on the tank, *T*, forces the brine to the evaporator, *E*, where because of the low pressure some of the water is vaporized thereby cooling the remaining brine in *E*. The cold brine is then forced by brine pump, *B*, through the refrigeration coils, to the tank, *T*. The high vacuum, in *E*, is maintained by the ejector, *J*, and the surface condenser, *C*.

Note.—Where Electric Energy Is Available At Low Rates, The Compression Process Is The Most Economical. In refrigeration systems where constant temperatures are desired, direct-current motors are often desirable for compressor drive on account of their speed controlling features. In ice-making plants, alternating-current motors are satisfactory as these plants can be run at full speed while in operation.

640. Refrigeration May Be Accomplished By The Vaporization Of Water At A Low Pressure. As stated in Sec. 317, the temperature at which water—or any liquid—boils depends directly on the pressure exerted upon the liquid. If the pressure is lowered sufficiently, water will boil at 32° F. Thus, refrigeration could be effected by using water in the arrangement shown in Fig. 551 provided a high vacuum could be maintained in the expansion coil, by some sort of apparatus located at the exhaust end, *A*. However, if a piston compressor were used for maintaining a vacuum at *A*, its piston displacement per pound of vapor would be absurdly great because of the large specific volume of steam at such low pressures. This difficulty has been overcome in the *Westinghouse-Leblanc water-vapor refrigerating machine* (Fig. 564) by using a steam-jet compressor, *J*, for compressing the water vapor instead of using a reciprocating compressor.

Explanation.—The ejector compressor, *J*, readily handles large volumes of water vapor. This machine is in its experimental stage and at present is used chiefly in marine work. It is believed however that its use will become more widespread. While temperatures below 32° F. can be obtained with this machine, its best economy is for temperatures between 35° and 50° F. It is well adapted to cooling the air in theatres and other large buildings.

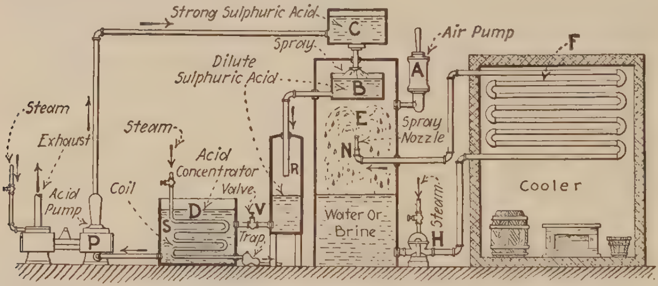


Fig 565.—Diagram of a sulphuric-acid vacuum machine. The air-pump, *A*, produces a vacuum in tank, *E*, causing some of the water liquid in *E* to evaporate. Sulphuric acid contained in *C*. flows down in the form of a spray into *B*. Since the acid has a great affinity for water the acid rapidly absorbs the vapor liberated from the liquid in *E*. The dilute acid flows through the pipes to the receiver, *R*. When *R* is filled, the valve, *V*, is opened and the dilute acid flows to the reconcentrator, *D*, where the water is evaporated from the solution by the steam coil, *S*. Pump, *P*, pumps the acid up to the tank, *C*. The brine solution is forced through the coil, *F*, and through the nozzle, *N*, by the centrifugal pump, *H*.

641. The Sulphuric Acid Refrigerating Machine, an arrangement similar to that of Fig. 565, was at one time used in the past. In this arrangement, sulphuric acid, because of its affinity for water, was used to remove the water vapor and produce the lower pressure in the evaporator. But the cost of operation was excessive due to the large amount of liquid pumped and the heat required to concentrate the acid.

NOTE.—IN THE COMMERCIAL WATER-VAPOR REFRIGERATING MACHINES THE WATER EVAPORATING, COOLS A BRINE SOLUTION WHICH IN TURN COOLS THE ROOM. This is done for several reasons: (1) It would be next to impossible to carry a high vacuum throughout the long cooling coil. (2) The water would tend to freeze if a temperature near 32° F. were reached. By evaporating part of the water from a brine solution in an evaporator—tank—the remaining solution may be cooled and then circulated under atmospheric pressure through the coils in the room to be cooled.

642. For Economical Operation Of The Vapor-refrigeration Processes All The Component Units Should Be Of Proper Size In Relation To One Another. In this respect they are similar to the units of steam power plant processes. In the steam power plant, for a certain output, a definite size boiler, engine and condenser are necessary. For best efficiency, these must be operated in such a manner that the boiler and condenser pressures are maintained at the values for which the engine was designed. To accomplish this the boiler must generate steam and the condenser must condense steam at the same rate that the engine uses it. The same principles must be observed in the refrigeration plant. For a certain output or capacity a definite size expansion coil, compressor—or absorption machine—and condenser are necessary.

643. For The Best Efficiency The Plant Must Be Operated In Such A Manner That The Proper Pressures Are Maintained in the evaporating coils and condenser. This is more important in refrigeration than in steam-power practice. The pressure in the expansion coils must be low enough so that the corresponding boiling temperature of the liquid refrigerant is below the temperature required in the cooled room. The pressure in the condenser must be high enough so that the corresponding liquefaction temperature of the refrigerant vapor will be higher than that of the circulating water. But the difference between the pressure in the condenser and that in the expansion coil must be kept as small as possible. The greater this pressure difference, the more work must be done by the compressor to bring the vapor from the one pressure to the other. In a steam engine more work is obtained in working through a greater pressure range, so in a compressor more work must be done in compressing through a greater pressure range. Also, in the absorption process more steam is used in heating to a higher pressure. In the compression process, the pressures in the expansion coil and condenser are regulated by the expansion valve and the compressor. In the absorption process these pressures are regulated by the steam flow to and the steam pressure in the generator coils, the concentration of the weak and strong aqua and by the speed of the aqua pump.

Note.—Many Of The Same Difficulties That Are Encountered In Steam Power Plants Are Also Encountered In Refrigeration Plants.—Expansion coils like boiler tubes must be kept clean to insure maximum heat transmission. Likewise, foreign (non-condensible) gases in the refrigerant increase the condenser pressure in refrigeration processes just as they do in steam condensers. In refrigeration condensers the non-condensible gases are taken out at intervals, instead of continuously by a pump as they are in steam-power-plant practice. In refrigeration plants, the effect of these troubles is, ordinarily, even more noticeable than in steam power plants.

644. Cooling By The Expansion Of Compressed Air Is One Of The Oldest Methods Of Mechanical Refrigeration. The "heat pumps" used are called *air refrigerating machines*, or *cold air refrigerating machines*. One type is called the *Allen dense-air refrigerating machine*. The cycle of an air refrigerating machine is explained in Sec. 432 and Fig. 384 shows a diagram.

Explanation.—The process is essentially as follows (see Fig. 566 and 384). Air is compressed in *C* (Fig. 566) to a high pressure. The heat which is imparted to the air by the compression is then removed by passing the compressed air, at constant pressure, through a cooling coil, *D*, which is surrounded by circulating water. The cooled compressed air is then admitted into an air-engine cylinder, *E*, where it is allowed to expand and do work. This expansion of the air causes a reduction in its temperature, due to the work being done at the expense of the internal energy (see Sec. 272). This cold expanded air is then discharged from *R* into the refrigerated room. Or it is passed from *R* through coils in the room to be cooled or it may be passed through coils immersed in a liquid, which in turn cools the room. The air from the refrigerated room or the coils, after there absorbing heat, again enters the compressor from *F* and the cycle is repeated. The work done by the air during the expansion in the air-engine cylinder, *E*, is transmitted through the main crankshaft, *S*, to the compressor cylinder, *C*. Thus the work done in steam cylinder, *L*, must be approximately only the difference between the work done by the compressor, *C*, and that obtained in the air-engine cylinder, *E*, plus the frictional losses.

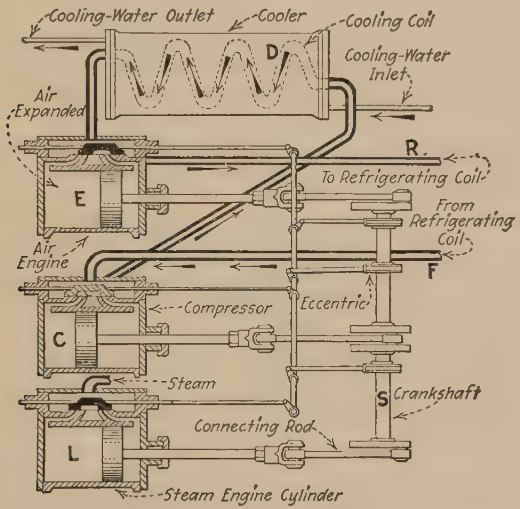


Fig. 566.—General arrangement of cold-air refrigerating machine.

Note.—Generally, The Same Air Is Continually Recirculated through coils to prevent the entrance of moisture into the system and the possible freezing of the moisture at the cold part of the cycle. Recirculation of the air also tends to increase the efficiency of the system.

Note.—This Method Of Cooling Is Not So Efficient As The Other Methods now in use. It also requires a much larger compressor than the vapor processes because of the low specific heat of air While this process has the above disadvantages, it is used to some extent aboard vessels due to the absence of any dangerous gas which may be injurious to the passengers and the food.

645. The Methods Of Calculating For Air Refrigerating Machines The Rise In Temperature During Compression And The Fall In Temperature During Expansion (assuming adiabatic changes in both the compression and the expansion, which is practically the case) are given in Sec. 275.

Example.—In a certain air-compression system it is found that the air entering the compressor has a temperature of 60° F., the admission pressure is 50 lb. per sq. in. abs., and the air is compressed to a pressure of 175 lb. per sq. in. abs. Assuming adiabatic compression and dry air what will be the temperature of the compressed air? Solution.—For polytropic changes, Sec. 275, the relation between temperatures and pressures is expressed by For. (236), $T_2 = T_1(P_2/P_1)^{\frac{n-1}{n}}$. Wherein: T_1 and T_2 = initial and final temperatures respectively in degrees Fahrenheit, absolute. P_1 and P_2 = initial and final pressures respectively in pounds per square inch absolute. For adiabatic changes, $n = k = 1.4$. Hence, substituting, $T_2 = (460 + 60)\ (175/50)^{\frac{1.4-1}{1.4}} = 520\ (3.5)^{0.285} = 520 \times 1.428 = 743°$ *F. abs.* or 283° *F.*

Example.—If the compressed air with a temperature of 283° F. as shown in the preceding example be cooled by circulating water to a temperature of 100° F. and then allowed to expand to the original pressure, what would be the final temperature? Solution.—Substituting in For. (236), $T_2 = T_1(P_2/P_1)^{\frac{n-1}{n}}$, the following is obtained, $T_2 = (100 + 460)(50/175)^{\frac{1.4-1}{1.4}} = 560 \times 0.286^{0.285} = 560 \times 0.7 = 394°$ *F. abs.* or $-66°$ *F.*

646. The Indirect Method Of Refrigeration is often used (Figs. 567, 568, 569 and 570). In the preceding sections of this division, only the direct-expansion method of refrigeration has been treated. In the *direct-expansion method* (Fig. 554) the expansion coils are placed in the room or substance to be cooled and the heat flows directly from the room or substance to be cooled to the refrigerant. In the *brine indirect method*, Fig. 569, the expansion coils are used to cool a brine solution, and the cooled brine is pumped through coils or tanks located in the room or substance to be cooled. In this system the heat flows from the

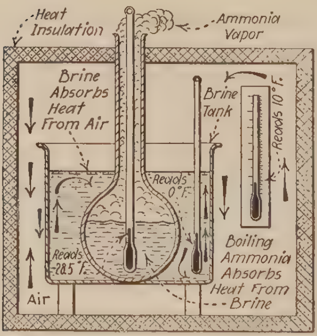


Fig. 567.—The elements of an indirect brine refrigerating system.

room which is to be cooled to the fluid and then to the refrigerant. There is another indirect system, called the *forced-air circulation* system (Fig. 570). In this system the air is cooled in a separate bunker room and the cooled air is forced through the cooler by means of a fan. This system is indirect in that the air is cooled outside of the cooler.

NOTE.—THE INDIRECT BRINE SYSTEM HAS SEVERAL ADVANTAGES AND DISADVANTAGES.—The chief advantage of the brine system is that "cold" can be stored in the brine, by cooling it to a low temperature. Thus a cooling effect can be produced by circulating the brine, even after the compressor has been shut down for some time. This is particularly desirable where excess refrigeration is required intermittently for short periods, such as in ice-cream making and milk-cooling processes. The brine system has another advantage that in it the ammonia circuit is confined to a small space and not allowed to enter the cooling rooms.

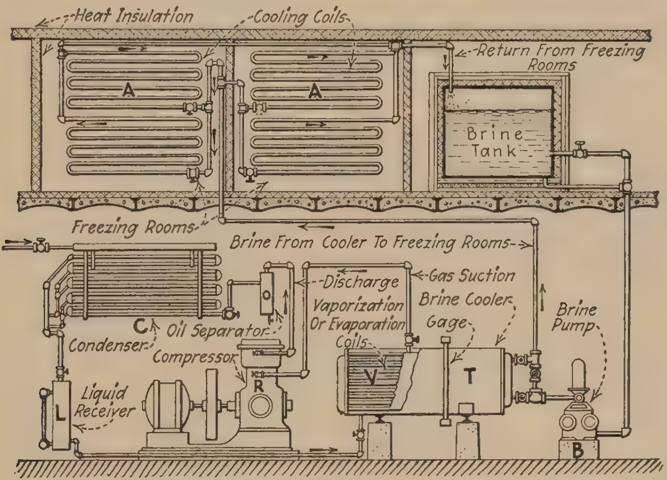


FIG. 568.—Typical indirect brine system with ammonia compressor.

Thus, should a leak occur in the expansion coil of a brine system, the ammonia cannot get into the cooled room, where it would injure the goods in storage and might cause fatalities. However, the indirect brine system has the disadvantage of a greater first cost and lower economy. Since the ammonia must first cool the brine, which in turn must cool the room, two temperature differences are required between that of the boiling ammonia in the vaporization coils and that of the refrigerated room, instead of one. To obtain the same room temperature with a brine system as with a direct expansion system, the ammonia in the brine system must boil at a lower temperature (lower pressure) which reduces the capacity of the compressor (if compression process) and lowers the economy. Ordinarily the indirect brine system is seldom used for plants which operate 24 hr. per day.

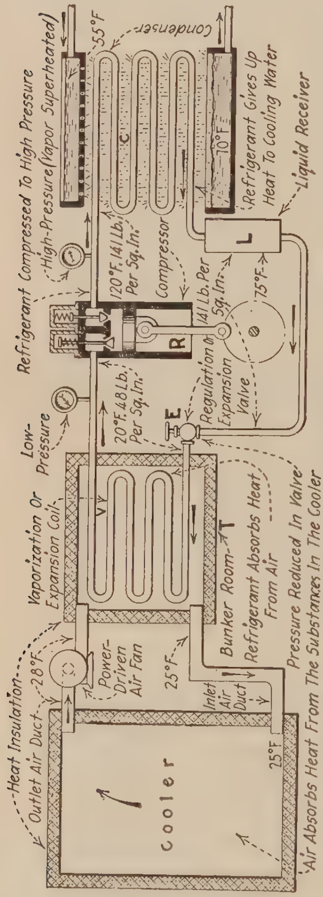

Refrigerant Compressed To High Pressure
High-Pressure (Vapor Superheated)
55°F
Condenser
C
70°F
Refrigerant Gives Up Heat To Cooling Water
Liquid Receiver
L
120°F. 141 Lb. Per Sq. In.
Compressor
R
141 Lb. Per Sq. In.
75°F
Regulation of Expansion Valve
E
20°F. 48 Lb. Per Sq. In.
Low-Pressure
Vaporization Or Expansion Coil
V
Bunker Room
T
Refrigerant Absorbs Heat From Air
Pressure Reduced In Valve
Air Absorbs Heat From The Substances In The Cooler
Heat Insulation
Outlet Air Duct
28°F
Power-Driven Air Fan
25°F
Inlet Air Duct
25°F
Cooler

FIG. 569.—Circuits of an indirect brine refrigeration system. The temperatures and pressures shown are reasonable ones but obviously these will vary with the design of the plant and local conditions. The pressures are absolute.

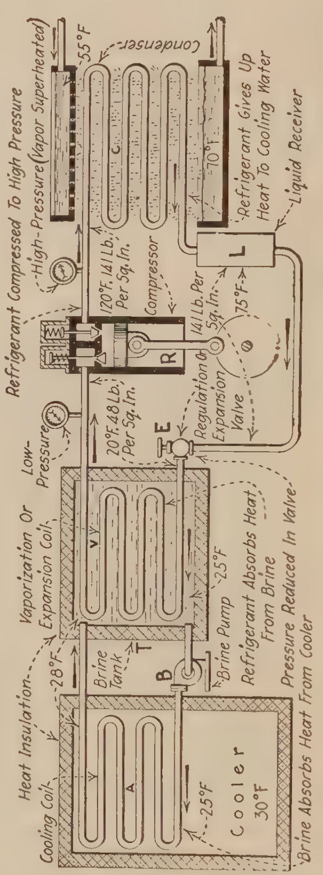

Refrigerant Compressed To High Pressure
High-Pressure (Vapor Superheated)
55°F
Condenser
C
70°F
Refrigerant Gives Up Heat To Cooling Water
Liquid Receiver
L
120°F. 141 Lb. Per Sq. In.
Compressor
R
141 Lb. Per Sq. In.
75°F
Regulation of Expansion Valve
E
20°F. 48 Lb. Per Sq. In.
Low-Pressure
Vaporization Or Expansion Coil
V
25°F
Refrigerant Absorbs Heat From Brine
Pressure Reduced In Valve
Brine Absorbs Heat From Cooler
Heat Insulation
28°F
Brine Tank
T
B
Brine Pump
Cooling Coil
A
25°F
Cooler 30°F

FIG. 570.—Circuit of indirect air or forced-air circulation refrigeration system. See Fig. 569 in regard to temperatures and pressures.

647. One Of The Chief Uses Of Refrigeration Processes Is For Making Ice (Fig. 571).—The ice-making industry has grown until it is one of the important ones of the country. While there are several systems of manufacturing ice, the principal one employed at present is the can system, either using distilled or "raw" (undistilled) water.

EXPLANATION.—IN THE "CAN" SYSTEM OF MAKING ICE, Fig. 572, cans, *C*, of rectangular cross-section are partly immersed in a brine tank, *T*, and filled with water. The brine, being cooled by the expansion coils, *E*, and circulated by the agitators, *A*, absorbs heat from the water in the cans. Ice is formed rapidly at first, around the insides and bottoms of the cans, but as the freezing progresses toward the center of the cans the rate of ice formation decreases. Since the ice is generally cooled to the temperature of the brine, *the heat that must be absorbed from 1 lb. of water to convert it into ice = (the heat required to cool the water to the freezing temperature) + (the latent heat of fusion of the water) + (the heat required to cool the ice to the temperature of the brine).* After the water in the cans has been frozen into ice, they are lifted out of the tank by the hoist, *H*. They are then warmed slightly on the outside with steam or hot water and the blocks of ice dumped out of them by the can dump, *D*, and thawing apparatus.

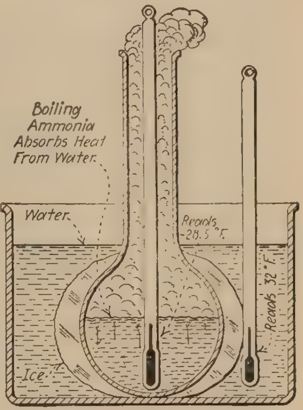


FIG. 571.—The elements of an ice-making system. This represents an elementary "plate" ice-making system (Sec 647) and does not apply to the can system.

NOTE.—EITHER "RAW" OR DISTILLED WATER CAN BE USED in the can system of making ice. In the distilled-water process, which is desirable where exhaust steam is available, the water is first distilled by using the exhaust steam and the cans filled with this distilled water. In the raw-water process, since raw water—undistilled water—contains air and impurities in solution, the water in the cans is agitated by bubbling compressed air through it (Figs. 573 and 574). This agitation removes the air dissolved in the water and brings the impurities in the water together into the central vertical cavity of the block of ice which is forming. From this cavity the impurities can be easily removed by syphoning them off and then refilling the hole with water. The raw water system is often used where no exhaust steam is available, as in electrically-driven plants.

NOTE.—THE PLATE SYSTEM OF ICE-MAKING (see Fig. 571 for elements) is used in some plants but is seldom installed at present because of the high first cost, greater head room necessary, and lower back pressure required. It is a raw water system, in which the ice is formed on a flat plate that is immersed in a tank of raw water. The hollow plate is arranged so that it functions as an expansion coil. The liquid ammonia is fed into it and the vapor is withdrawn from it. The ice cake formed is large and irregular in size.

EXAMPLE.—How much heat must be absorbed from 1 lb. of water at 70° F. to change it into ice, at the temperature of the brine leaving the

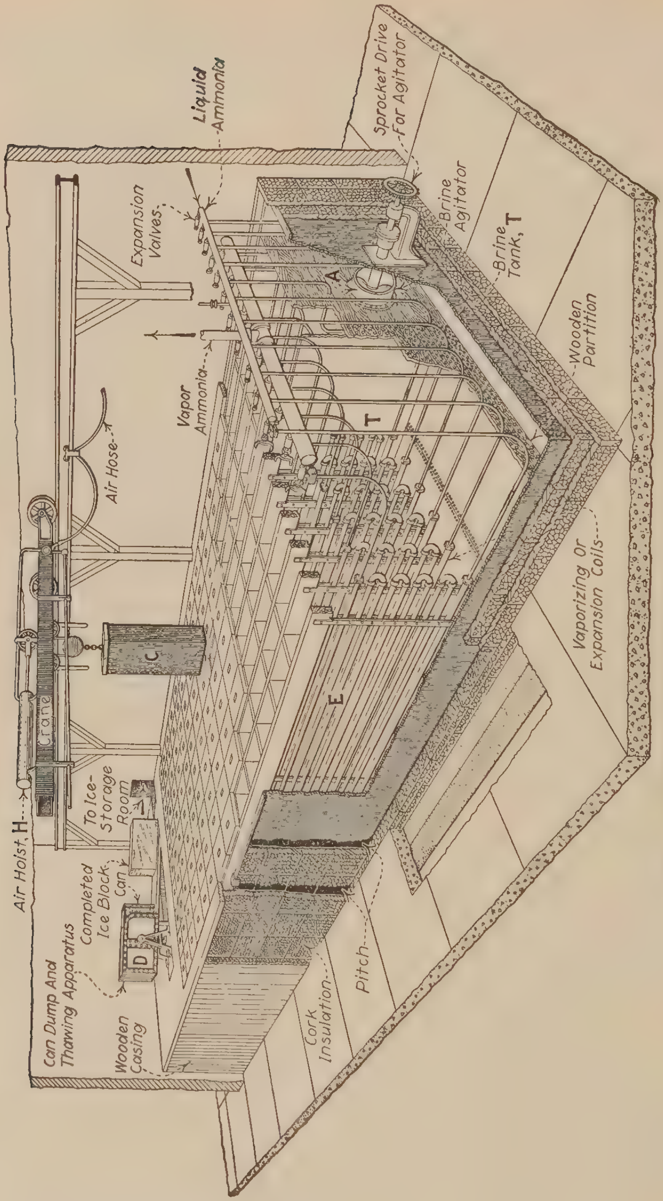


Fig. 572.—Showing the construction of the Triumph freezing tank.

tank, 16° F. Assume specific heat of ice as 0.5. SOLUTION.—*Heat absorbed* = *Heat required to cool water to the freezing temperature* + *Latent heat of fusion* + *Heat required to cool ice to brine temperature* = (70 − 32) +144 + [(32 − 16) × 0.5] = 38 + 144 + 8 = 190 *B.t.u. per lb. of water or ice.*

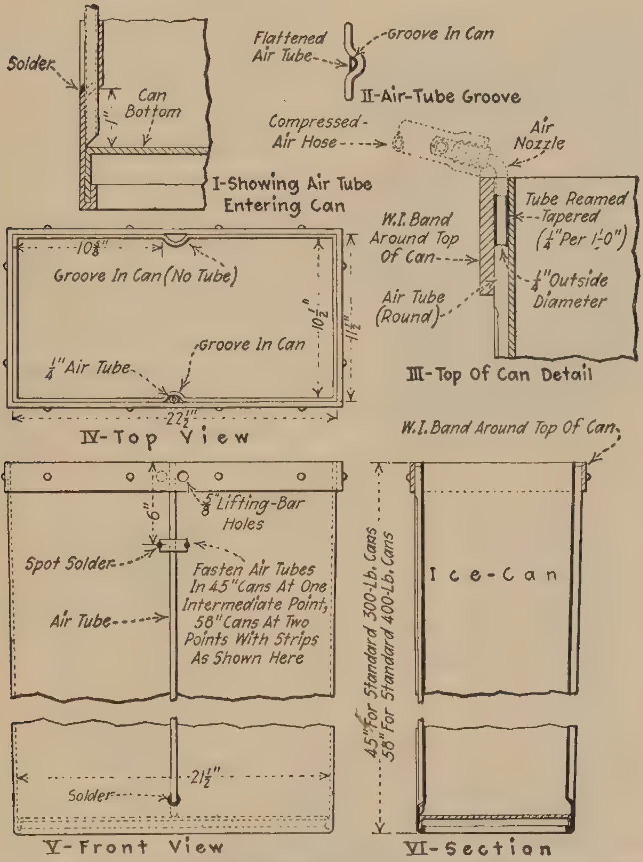


FIG. 573.—Diagram showing typical construction of cans for raw-water ice. The tube for conveying the compressed air extends almost to the bottom of the can.

648. The Unit Of Capacity In Refrigeration Is The "Ton Refrigeration."—Refrigeration, being essentially a heat-transfer process, its capacity is measured by the quantity of heat extracted per unit of time. In steam boiler practice the unit of heating capacity (33,749 B.t.u. per hr., Sec. 500) has been given the arbitrary term "horsepower." Likewise in refrigeration practice the unit of capacity has been given the term "ton refrigeration," and is equivalent to a rate of cooling of 12,000 B.t.u. per hr. It has a somewhat rational basis. If the latent heat of fusion of ice is taken as 144 B.t.u., which is nearly correct, then *the heat required to melt one ton (2,000 lb.) of ice = 2,000 × 144 = 288,000 B.t.u.* Now if this heat was absorbed in one day (24 hr.) the heat would be transferred at the rate of 288,000 B.t.u. per 24 hr. or 12,000 B.t.u. per hr. or 200 B.t.u. per min. Since the rate of transferring heat is not necessarily the same in all parts of the system, it is desirable to establish a standard place of measurement. Thus a system is said to have "one ton refrigeration capacity" when it is so proportioned that the refrigerating fluid in the expansion coils will under normal specified temperature and pressure abstract heat at the rate of 12,000 B.t.u. per hr. or 200 B.t.u. per min.

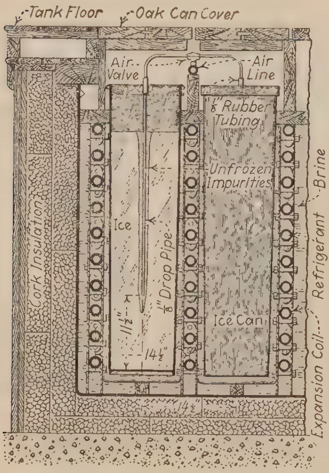


Fig. 574.—Cross-section of ice cans, showing low-pressure air agitation system with double down pipes. (*The Robert J. Berryman Co.* This shows an adaptation of a distilled-water brine tank to a raw-water system.)

Note.—The Ice-making Capacity Of A Plant Is Less Than The Ton Refrigeration Capacity.—The ton refrigeration capacity considers only the latent heat of fusion of ice. In ice making, the water must be cooled to the freezing temperature, and usually the ice is cooled to the temperature of the outgoing brine. Thus, more than 144 B.t.u. must be absorbed to produce one pound of ice. The ice-making capacity is not a definite rating since it depends on the losses and the temperatures of the water and finished ice. It usually is about 60 per cent. of the ton refrigeration capacity.

649. The Power Consumed by a mechanical-refrigeration plant varies from 1 to 2.5 i.hp. per ton of refrigeration. The greater the difference between the compressor suction and discharge pressures, the greater will be the power required for a ton refrigeration. Average economies will be near 25 lb. of water freezing effect per pound of coal. This applies to either compression or absorption processes for all vapor refrigerants, since the power required for a ton refrigeration is about the same for all vapors. The air compression processes are not so efficient and they probably average 5 lb. of water-freezing effect per pound of coal. Ice making, as stated in the preceding note, requires more refrigeration than the water-freezing effect referred to herein.

Note.—The Coefficient Of Performance Of Refrigeration Machines = (*heat extracted from the cold body*) ÷ (*the indicated work done by the compressor*). Both terms must be expressed in either British thermal units or foot-pounds per unit of time. See also Sec. 405.

650. The Liquid-air Process operates on the same general principles as does the air refrigerating machine. By means of this process, low temperatures can be obtained and air can be liquefied. A diagrammatic sketch of the process is shown in Fig. 575.

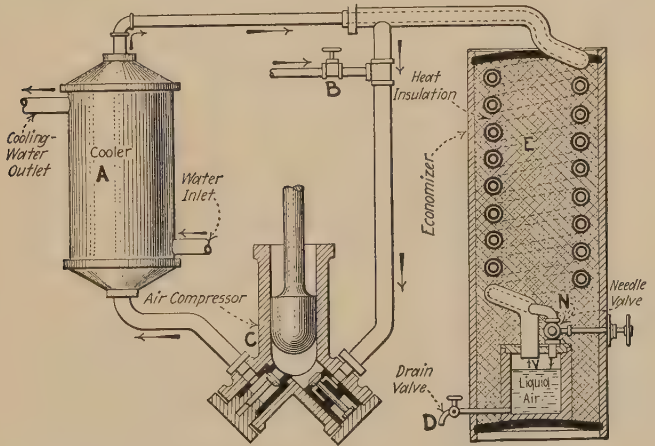


Fig. 575.—Diagrammatic view of the Linde liquid-air apparatus.

Explanation.—An air compressor, *C*, Fig. 575 (usually of the four-stage type, the air being cooled between stages to prevent too great an increase in temperature) compresses the air to a pressure of about 3,000 lb. per sq. in. From the compressor the air is carried to the cooler, *A*, where it is cooled by cold water to almost the temperature of the water, its pressure remaining at about 3,000 lb. per sq. in. After passing through the cooler, the air is carried to the "economizer," *E*. This consists of a double-pipe coil (one pipe being within the other) enclosed in a well heat-insulated tank. At the bottom the two coils separate, but both enter the same vessel, *V*, the inner coil being provided with the needle valve, *N*, by means of which the air flow is regulated.

As the compressor continues to operate the compressed air flows through the inner coil, through the needle valve, *N*, in which it suffers a throttling expansion (constant heat, Sec. 260) to the low (approximately atmospheric) pressure of the vessel, *V*. In expanding through *N* the air is cooled, and the now cold air is then drawn out of *V* through the outer coil of the economizer into the compressor. In flowing through the outer coil of the economizer, *E*, the outgoing cold air cools the incoming air in *E*. The temperature of this incoming air after expansion into *V* is lower than was that of the outgoing air which preceded it. Thus in *E* both the incoming and outgoing air temperatures are gradually reduced as the compressor continues to circulate the air in the system. The process is accumulative and, as the compressor continues to operate, the temperature falls until the liquefying temperature is reached in *V*. A portion of the air will thereafter condense as it flows through *N* and will collect in *V*. As some air is condensed into a liquid, more air must be admitted (in small quantity) to the system through the valve, *B*, to take the place of the liquefied air. The liquid air can, when formed, be drawn off through the valve, *D*.

QUESTIONS ON DIVISION 18

1. Define *refrigeration*. Why is it treated in a book on practical heat?
2. Name several uses of refrigeration.
3. What are the requirements of a good refrigeration system?
4. Define *refrigerant*. *Refrigerator*.
5. Why are the walls of ice-boxes and cold-storage rooms composed of heat insulators?
6. Name several good heat insulators.
7. Into what two classes may refrigeration processes be divided?
8. What are the three important natural refrigeration processes and what is the underlying principle of each?
9. Where is cooling by surface evaporation used?
10. What is the minimum temperature obtainable by surface evaporation?
11. For what classes of refrigeration is cooling with ice, best adapted?
12. Draw a sketch of a room cooled with ice and explain the essential features.
13. What substance is used as the heat carrier in the refrigeration processes where the melting of ice produces the cooling effect?
14. Upon what factors does the success of a cooling process by means of ice depend?
15. What is a freezing mixture? How are freezing mixtures used in refrigeration?
16. Where should the cooling coil be placed in the cold-storage room?
17. Into what two types can mechanical refrigeration processes be divided? Define each.
18. Draw a diagrammatic sketch of a cold-air refrigerating machine and explain its operation.
19. Upon what principle are the vapor refrigerating processes based?

20. In what two ways may temperatures below atmospheric be obtained by the use of vapors?

21. Explain the operation of a water-vapor refrigerating machine. What is the feature of the Westinghouse Le Blanc water-vapor refrigerating machine?

22. Draw a sketch of an elementary ammonia refrigerating process, and explain its operation. Why is this arrangement not used in commercial vapor refrigeration processes?

23. Name the liquids frequently used in commercial vapor machines. Give the king of conditions for which each one is best adapted.

24. By what two methods may the vaporized liquid be restored to its initial liquid condition?

25. What are the essential parts of a vapor compression refrigerating process and explain the use of each?

26. Explain why a compressor is necessary in a vapor compression refrigeration process.

27. Wherein does the vapor absorption process differ from the vapor compression process?

28. Draw a sketch of an elementary vapor absorption process and explain its operation.

29. Describe the operation of a commercial vapor absorption process. How does it differ from the elementary process?

30. How can the increase in efficiency obtained by the use of the exchanger and rectifier be explained?

31. What are the relative merits of the absorption and compression processes?

32. Upon what conditions does the economical operation of vapor processes depend?

33 Explain the brine or "indirect" system. Discuss its advantages and disadvantages What is the direct system?

34. Describe the can system of ice making, when using raw water. Describe the plate system.

35. Define a *ton refrigeration.* Explain the difference between ton refrigeration capacity and ice-making capacity

36. How much power is generally required per ton refrigeration?

37. What is meant by the coefficient of performance?

38. Describe the liquid-air process.

PROBLEMS ON DIVISION 18

See also the refrigeration problems in and which follow Div. 12.

1. The temperature of the atmosphere is 70° F. and its relative humidity is 0.40. What is the lowest temperature that can be obtained by surface evaporation?

2. An ice-box with a surface of 520 sq. ft. has a leakage of 0.7 B.t.u. per sq. ft. per hr. The heat that must be absorbed from the contents and the air changes is 900 B.t.u. per hr. How much ice will be needed every 24 hr.? Assume latent heat of ice as 144 B.t.u.

3. Air at 100 lb. per sq. in. abs. and a temperature of 100° F., is allowed to expand in a cylinder and do work on a piston until the pressure falls to 40 lb. per sq. in. abs. Assuming adiabatic (frictionless) expansion, what is the temperature of the expanded air?

4. If water is to boil at 50° F., what must be the pressure of the water?

5. If 10,000 B.t.u. must be absorbed from a room per hour, how many pounds of anhydrous ammonia at a temperature of 80° F. must be vaporized at a pressure of 29 95 lb. per sq. in. abs. each hour? Assume ammonia vapor leaves dry and saturated.

6. If the temperature of the condenser cooling water is 70° F., what is the minimum condenser pressure allowable in a ammonia compression process?

7. If the water is at 70° F., how much heat must be absorbed from 1 lb. to change it into ice, when the ice is cooled to a temperature of 20° F.

8. If in an actual plant 260 B.t u. are absorbed to freeze 1 lb. of ice, what is the capacity in tons refrigeration required to produce 5 tons of ice in 24 hr.?

9. In a certain plant, the compressor does 2.0 hp of work for a ton refrigeration cooling effect. What is the coefficient of performane?

DIVISION 19

INSTRUMENTS

651. Instruments For Measuring Heat Effects will be discussed in this division. Strictly speaking, heat cannot be measured. But certain of its effects, such as temperature, pressure, volume change, and the like, may, with properly designed instruments, be quite accurately measured in units (discussed in preceding divisions) which have been adopted for this purpose. Quantitative consideration of the values, stated in terms of these units, which may be obtained under different heat conditions affords much information which is almost invaluable to the engineer. In fact, the material in the preceding divisions of this book is based largely on data which has been or may be obtained only through the use of heat-effect measuring instruments of the different types.

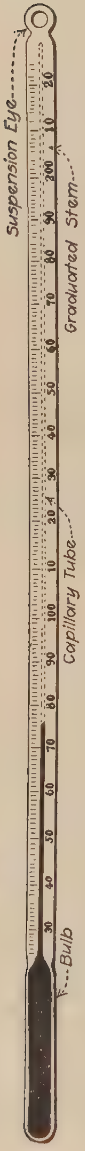


Fig. 576.—Engraved glass thermometer.

Note.—The Characteristics Of The Different Instruments Which Will Be Discussed in the following sections are, in most cases: (1) *applications*, (2) *operating principle*, (3) *installation*, (4) *accuracy*, (5) *maintenance*, and (6) *calibration*.

652. A Thermometer (Fig. 576) is a device for measuring temperature (Sec. 57). All temperature-measuring devices are not, however, called thermometers; see Sec. 661. The term *thermometer* is usually applied to those temperature-measuring instruments which depend for their operation upon the expansion or contraction of a fluid or solid, and which are capable of indicating temperatures ranging from about −150 to +1,000 deg. fahr. For measuring extremely-high or low temperatures, devices called *pyrometers* (Sec. 661) are ordinarily employed. For principles, method of construction, and the different scale-systems of thermometers, see Secs. 57 to 64.

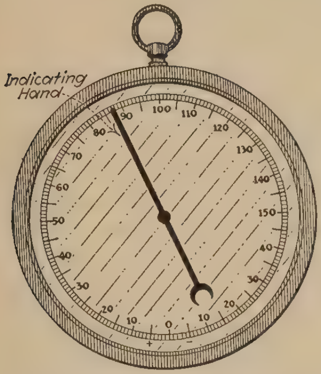


Fig. 577.—Front view of bi-metallic thermometer. (*Standard Thermometer Co.*, Boston, Mass.)

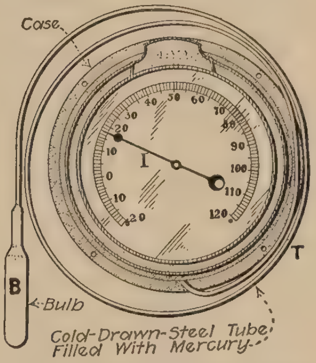


Fig. 578.—Remote-reading indicating thermometer. The bulb, *B*, is to be located at the point at which the temperature is to be taken.

653. Thermometers May Be Divided Into Two General Classifications: (1) *Indicating thermometers* (Figs. 576, 577 and 578), which indicate the temperature existing at the location under consideration. (2) *Recording thermometers* (Fig. 579), whereby the temperatures obtaining at all of the different instants throughout a certain time period are recorded on a chart. Indicating thermometers, of different types, may be obtained. The temperature change may be indicated by virtue of the expansion or contraction of either a solid, a liquid, or a gas. The operation of recording thermometers (Fig. 591) usually depends upon the expansion of a liquid, a gas, or a vapor. Mercury or alcohol are the liquids which are ordinarily used in indicating thermometers. For discussion of the

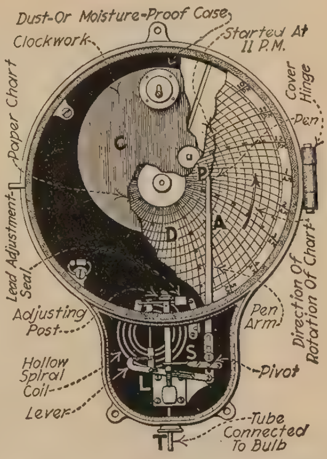


Fig. 579.—Remote-reading mercury recording thermometer. (*Taylor Instrument Co.*, Rochester, N. Y.)

various types under each of the above classifications, see following sections.

654. Mercury Or Alcohol Indicating Thermometers (Figs. 580 and 581), which are especially designed for convenience in determining temperatures, within the previously specified thermometer temperature ranges (Sec. 652), for practically any industrial service, are regularly manufactured. For extremely accurate determinations, a thermometer, which has the graduations engraved on the glass stem (Fig. 516) should be used. If the nature of the work is hazardous as to glass breakage, an armored thermometer (Fig. 582) should be employed. For temperature determinations where facility of reading and protection from breakage is more important than extreme accuracy, the thermometer-bulb and stem are secured (Figs. 583 and 584) to a wooden or metallic

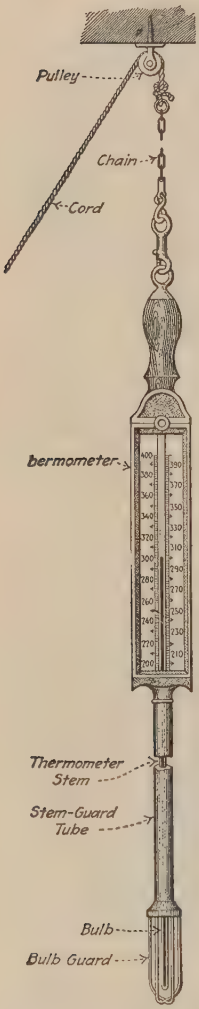


Fig. 580.—"Handled" thermometer suspended for use in open kettle.

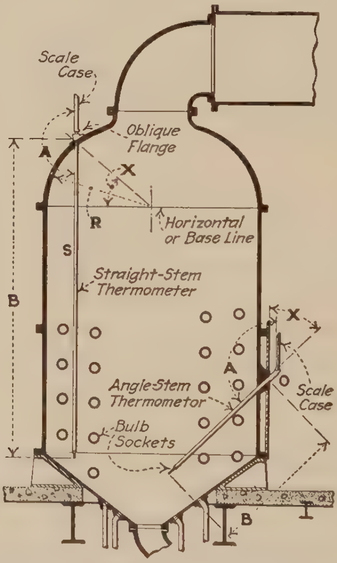


Fig. 581.—Straight stem (S) and oblique stem (O) thermometers equipped with oblique flanges and mounted on a digester. (*Taylor Instrument Co.*)

mounting. The graduations on the scale, which is held on or which is stamped in the mounting, are made extremely large, and that part of the glass stem which is visible from the front nearly always is so shaped (Fig. 584) as to magnify the liquid column in the glass tube.

Note.—For Measuring The Temperature Of A Confined Substance, such as steam or a liquid in a pipe line or tank, a *thermometer well* (Fig. 585) may be screwed (Fig. 586) into a tapped hole in the pipe or tank. To insure that the thermometer-bulb will not be air-jacketed and that it will be at the same temperature as the fluid, the temperature of which is being measured, the well is filled with mercury (or oil), and the thermometer-bulb is then placed in the liquid-filled well. Another type of thermometer which is used for the same purpose, wherein the thermometer-mounting is rigidly fastened to the well is shown in Fig. 587. This construction is generally employed for permanent installations. Thermometers, of this general type, are available which have dimension B (Figs. 581 and 588) equal to a maximum of about 5 ft., and angle A varying from 15 to 180 deg.

655. Indicating Thermometers Of The Dial-type (Figs. 577 and 589) which operate on the bi-metallic expansion principle (Sec. 188), are not, ordinarily, highly accurate unless very carefully and expensively constructed. Low-priced thermometers of this type are particularly applicable for the approximate determinations which are satisfactory in residences and offices. They are rugged in construction, and not so easily broken as are glass mercury thermometers. The usual temperature range is from about -40 to $+160°$ F.

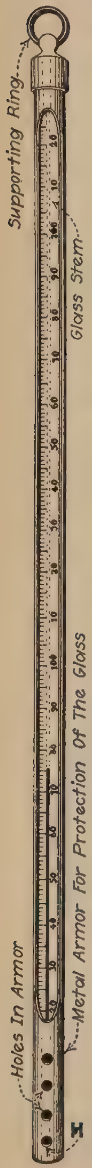


Fig. 582.—Armored thermometer. The holes, *H*, in the armor are to permit intimate contact between the thermometer bulb and the substance in which it is immersed.

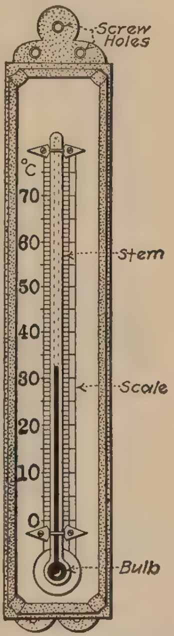


Fig. 583.—Thermometer mounted on metal case.

NOTE.—THE PRINCIPLE OF THE BI-METALLIC, OR THERMOSTATIC-METAL, THERMOMETER has been explained in Sec. 188. If such a thermostatic-metal strip be coiled into a spiral (Fig. 590), the metal strip will, if its temperature is changed, tend to become more nearly straight or it will tend to curve more, depending upon the metals, their arrangement, and the temperature change. If the strip has a tendency to

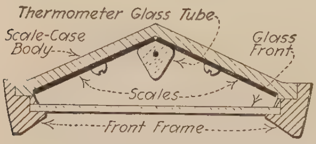


FIG. 584.—Transverse section through a protecting thermometer-scale case.

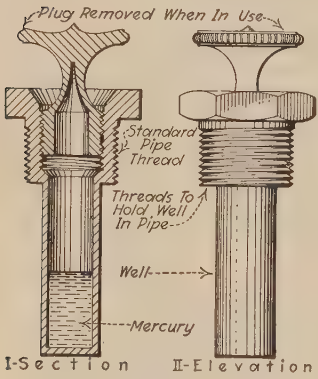


FIG. 585.—Thermometer well.

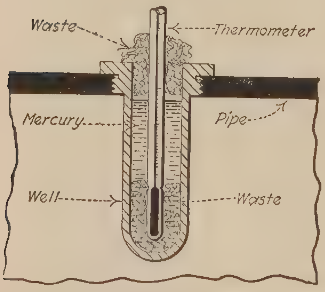


FIG. 586.—Thermometer in well protected by waste.

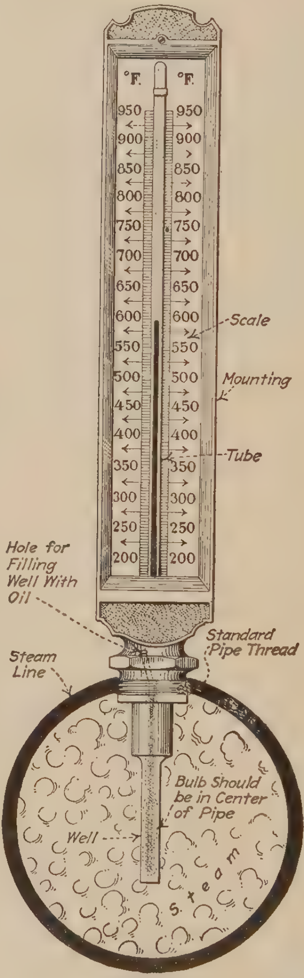


FIG. 587.—Thermometer with socket for insertion in steam line. (*Taylor Instrument Co.*)

straighten, the diameter of the spiral (Fig. 590) will be increased, and hence its circumference will be increased. Since the lineal length of the spiral strip remains nearly constant, this increase and decrease in circumference will, if one end of the spiral is held stationary, cause the other end to move along the circumference. By providing a number of turns as S, Fig. 589, this movement will be greatly increased. The loose end of the spiral is connected to a gear (G, Fig. 589) which operates to rotate the indicating hand over the dial (Fig. 577). With proper calibration, the temperature of the medium surrounding the coil is thereby indicated.

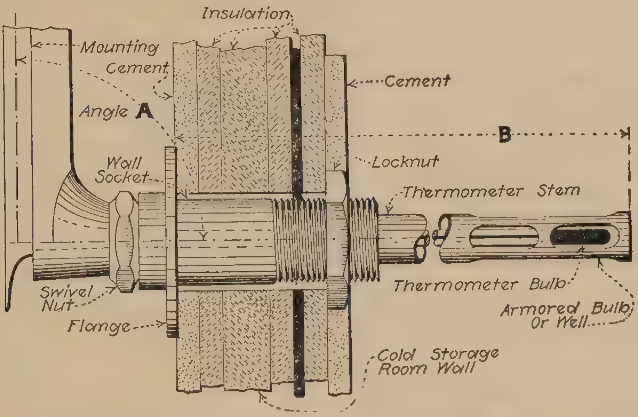


FIG. 588.—Installation of thermometer in cold-storage room.

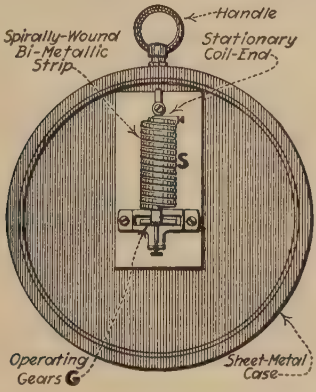


FIG. 589.

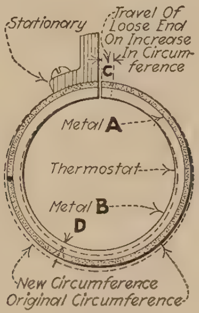


FIG. 590.

FIG. 589.—Rear view of bi-metallic thermometer of FIG. 577.

FIG. 590.—Top view of spiral showing action of circular thermostat. (*A* an *B* are different metals. The increase, *C*, in circumference is about π or 3.14 times the increase in diameter, *D*.)

656. A Remote-reading Thermometer (Fig. 578) is one which has a long metallic capillary tube, *T*, that connects the bulb, *B*, to the actuating mechanism which is within the case. The length of this capillary tube may vary from a few inches to about 100 ft. With this instrument, the bulb, *B*, is located at the point (which may be relatively inaccessible) where the temperature is to be measured and the indicating portion, *I*, of the instrument is mounted where it may be read conveniently. Remote-reading thermometers may be purchased in either the recording or the indicating type. They are capable of operating over temperature ranges of from about −40 to +1,000° F. The substance contained in the bulb and capillary tube may be either a liquid, a vapor, or a gas. In one make of these thermometers (the Bristol) the temperature ranges for the different media are liquid, −60° to +150° F; vapor, +90° to +500° F; gas, −60° to +800° F.

657. A Recording Thermometer (Figs. 579, 591 and 592) automatically plots a graph of temperature against time. In many applications, such as core, enameling, and japanning ovens, cold storage rooms, drying rooms, and the like, the final quality of the product depends upon certain heat processes. In nearly every heat-treating process there are predetermined limits within which the temperature must be maintained for given lengths of time. Frequently any variation from these will seriously damage the product. By using a recording thermometer, a complete and continuous temperature record may be obtained. The temperature range of recording thermometers is from about −40 to +1,000° F. Instruments of this type may, for low-temperature ranges, be either self-contained (wherein the bulb is contained within the instrument), or, for all temperature ranges, they may be remote-reading.

EXPLANATION.—THE MECHANISM OF A REMOTE-READING MERCURY RECORDING THERMOMETER is shown in Figs. 579 and 591. The spiral tubular coil, *S*, is connected to the remote bulb, *B*, by the tube, *T*. The bulb and tube are identical with that in Fig. 578. Mercury, which is the actuating medium, fills the bulb, extends through the fine bore in the flexible tube, and through the fine bore of the coil *S*. Upon being heated or cooled, the mercury in the bulb expands or contracts and the pressure thus produced is transmitted by the mercury column in the tube to *S*. This causes the free end of *S* to move (Sec. 677). This free end of *S*, by means of the lever, *L*, operates the pen-arm, *A*.

Thus *A* moves to the right as the temperature increases and to the left as it decreases. The chart, *D*, being properly graduated, the temperature at the bulb is indicated by the position of *A*. The chart, *D*, is rotated by the clock-movement, *C*, so that *D* makes, say, one revolution in 24 hr. Suppose at 11 p.m. the apparatus is started, and the chart is so adjusted that the 11-p.m. line is directly under the inked pen point, *P*, which is carried on *A*. Then 24 hr. later, the 11-p.m. line will have again rotated around to a position under the pen point. A complete and continuous 24-hr. temperature record is thereby provided.

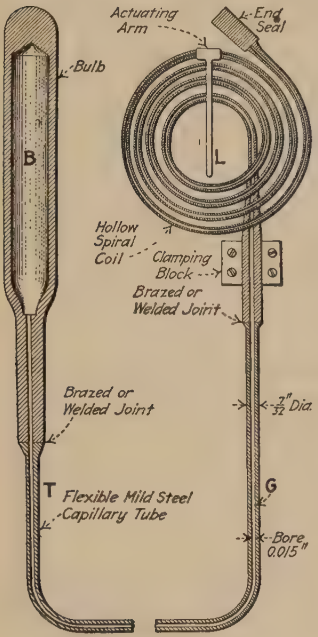


Fig. 591.

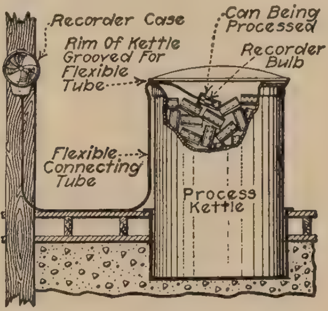


Fig. 592.

Fig. 591.—Mercury-filled steel-tube system of a mercury recording and index thermometer. (*Taylor Instrument Co.*) The volume of mercury in the bore, *G*, is reduced to a negligible percentage of the whole by inserting a wire, which nearly fills it, through the bore.

Fig. 592.—Recording thermometer to record temperature inside can while being processed.

658. The Calibration Of Thermometers is usually effected by comparison with a secondary standard. A secondary-standard thermometer is one that has been calibrated against a primary-standard gas thermometer. Any thermometer manufacturer, and also the U. S. Bureau Of Standards, Washington, D. C., have suitable apparatus for doing this work The charge is a nominal one of about 25 cents per calibration.

659. To Check The Graduations Of Mercury Thermometers As To The Boiling Point And The Freezing Point Of Water, the following method, which is sufficiently accurate for all power-plant determinations, may be used: Suspend the thermometer (Fig. 70) so that it will be entirely surrounded, up to the reading point, in the vapor of pure boiling water at atmospheric pressure. Note the reading. Also note the then-existing atmospheric pressure as shown by a barometer. From a steam table (Sec. 394) ascertain the actual boiling point for water at the existing atmospheric pressure. The difference will be the error in the position of the boiling point. Now surround the thermometer to the reading point with a mixture of water and ice. The difference between the reading thus obtained and the 32° mark (Fahrenheit scale) will be the error in the location of the water-freezing point on the thermometer.

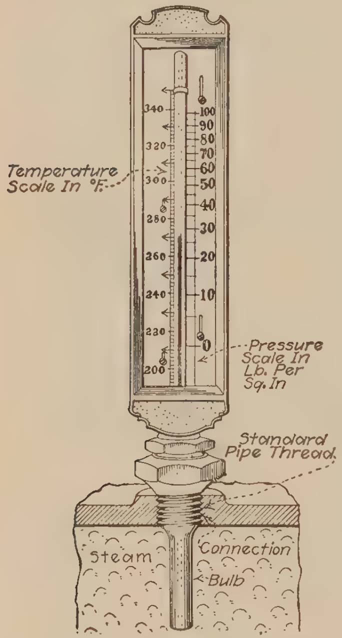


Fig. 593.—Thermometer graduated to read temperature in degrees Fahrenheit and saturated-steam pressure in pounds per square inch gage.

Note.—Thermometers Should, To Insure Accurate Temperature Readings, Be Calibrated Frequently.—By continued use, the alternate cooling and heating of the bulb will effect a change in the coefficient of expansion of the glass. This will, unless corrected by frequent calibration, result in erroneous readings. A thermometer is usually calibrated while immersed up to the point calibrated. When thermometers are so used that it is impossible to obtain such immersion, a *stem correction* may, for Fahrenheit thermometers, be applied by using the following formula:

(378) *Stem correction* = 0.000,088 × (*No. of degrees projecting*) × (*Thermometer reading* − *Mean temperature of emergent stem*).

Glass-tube thermometers are made which are accurate to within about 0.01° F.

NOTE.—A THERMOMETER MAY BE GRADUATED IN ANY DESIRED SYSTEM.—Those systems, as explained in Sec. 59, which are most frequently used are the Fahrenheit and the Centigrade. The relation which exists between the temperature of saturated steam and the steam pressure (Sec. 315 and Table 394) permits a thermometer to be calibrated (Fig. 593) both in degrees and in pounds per square inch. Such a thermometer, when used to measure the temperature of *saturated* steam (Sec. 354), also provides an accurate pressure gage.

660. Certain Precautions Should Be Observed In The Use Of Thermometers.—The location of the thermometer bulb should be such that intimate contact will be provided between it and the substance the temperature of which is being determined. If the bulb is located in a "pocket" or is in contact with a containing wall or other obstruction, erroneous readings will usually result. A thermometer which is used in a well (Fig. 586) should be kept from contact with the metal by waste. A thermometer should not be carried bottom end upward. It should never be subjected to temperatures which will cause the indicator to pass beyond the highest temperature graduation.

NOTE.—IN IMPORTANT TESTS WHERE TEMPERATURE DETERMINATIONS ARE REQUIRED, ALL THERMOMETERS SHOULD BE CALIBRATED AT THE BEGINNING AND AT THE END OF THE TEST.—They should be calibrated at the beginning so that, in the event one is broken during the test, the data which has been obtained with it will not be uncertain. They should be calibrated at the end to determine if any change has occurred during the test. A reserve of calibrated thermometers should be available for any important test. Then, if any thermometers are broken during the test, others may be substituted without interfering with its progress.

661. A Pyrometer Is An Instrument Especially Adapted For Determining Extremely High Temperatures.—But, when suitably designed, a pyrometer may also be utilized effectively for relatively low temperature determinations. For measuring temperatures of from about 1,000 to 3,600° F. pyrometers are required because these high temperatures are above the range of thermometers (Sec. 652). Pyrometers are applicable to such heat-treating processes as are found in the ceramic industries, steel mills, blast furnaces, glass plants, cement plants, foundries, gas plants, oil refineries, and the like. They are also used. in steam-power plants, for determining the flue-gas and other temperatures in the various passes in the boiler, stack, and furnace.

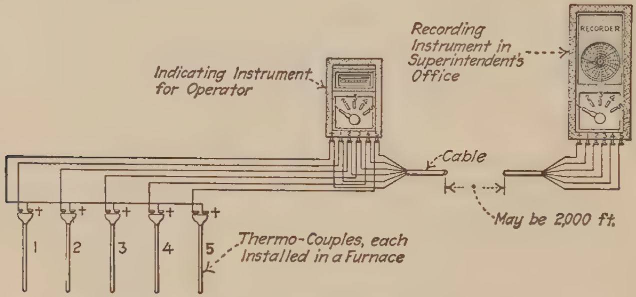

Recording Instrument in Superintendent's Office
RECORDER
Indicating Instrument for Operator
Cable
May be 2,000 ft.
Thermo-Couples, each Installed in a Furnace
1
2
3
4
5

Fig. 594.—Schematic diagram of thermo-electric pyrometer installation.

662. The Principal Types Of Commercial Pyrometers are: (1) *Thermo-electric pyrometers.* (2) *Direct-radiation pyrometers.* (3) *Resistance pyrometers.* (4) *Optical pyrometers.* (5) *Seger cone pyrometers.* Each will be discussed briefly in the following sections.

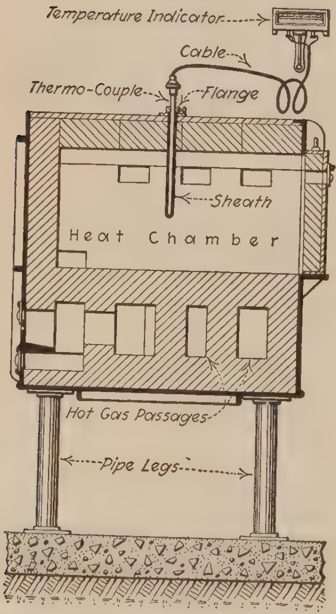


Fig. 595.—Thermo-electric pyrometer installed in an oil-burning furnace.

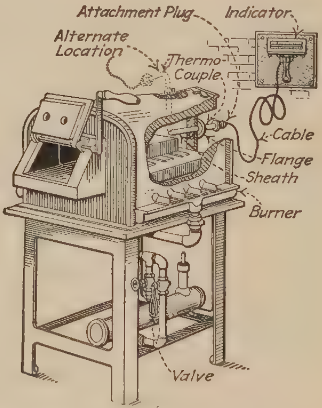


Fig. 596.—Thermo-electric pyrometer applied to a gas furnace.

663. The Thermo-electric Pyrometer Is Well Adapted To Multi-point Temperature Determinations.—As suggested in

Fig. 594, there may be installed in each of a number of furnaces, one thermo-couple which is connected to an indicating pyrometer located near the furnace. Also, each thermo-couple can be connected to operate a multi-recording pyrometer which may be located in the superintendent's office. Thus the furnace-operator may, by closing the proper switch, determine the temperature of any furnace. Also, the superintendent is provided with a continuous temperature record. The recording pyrometer, or *pyrograph*, may be 2,000 ft. or more from the furnaces. Figures 595, 596 and 597 show industrial applications.

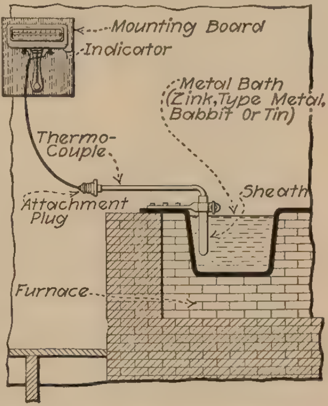


FIG. 597.—Thermo-electric pyrometer indicating temperature of a molten-metal bath.

664. The Principle Of The Thermo-electric Pyrometer (Fig. 598) is based on what is known as the *thermo-couple*. If two wires of different metals (Fig. 599) are connected at A and B, and one of the junctions, as B, is heated so that its temperature is greater than the temperature of A, an effective electromotive force will be generated, at the junctions which is proportional to the temperature difference between A and B, and an electric current will, thereby, be made to flow in the circuit. If a suitable electric measuring instrument such as a milli-voltmeter (E, Fig. 600) is interposed in the circuit, the generated voltage may be read thereon. Since the voltage generated by such an apparatus is proportional to the tem-

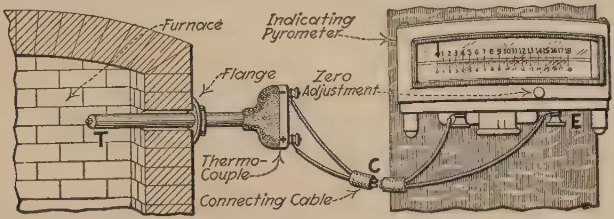


FIG. 598.—Thermo-electric pyrometer, showing installation of a thermo-couple.

perature difference between the cold and hot junctions, the scale of the milli-voltmeter may be graduated to read the temperature directly in degrees.

665. A Commercial Indicating Thermo-electric Pyrometer (Fig. 598) consists of a properly protected thermo-couple, *T*, the connecting cable, *C*, and an electrical voltmeter, *E*, which is graduated to read in degrees of temperature. The bare thermo-couple (Fig. 601) should, before it is exposed to high temperature, be enclosed in some sort of protecting tube (Figs. 602 and 603). These protecting tubes may be of various materials, such as iron, copper, nickel, chromium, quartz, porcelain, firebrick, graphite, or silica, depending upon the service for which they are to be used.

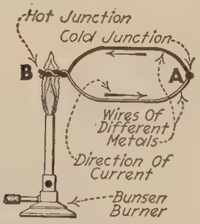


Fig. 599.—A thermo-couple. (A difference in temperature between *A* and *B* generates an e.m.f. which is proportional to the temperature difference.)

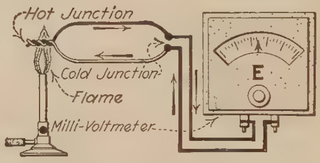


Fig. 600.—Principle of the thermo-electric pyrometer.

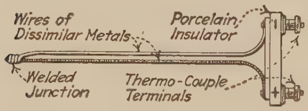


Fig. 601.—Bare thermo-couple.

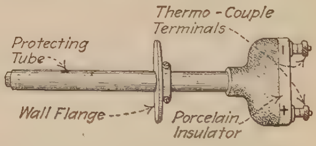


Fig. 602.—Thermo-couple enclosed in protecting tube.

Note.—The Metals Of Which Pyrometer Thermo-couples Are Made may be divided into two classes: (1) *Base metals.* (2) *Rare metals.* The base-metal thermo-couples are usually made of nickel-alloy wire. They are suitable for use in measuring temperatures up to about 1,800 or 2,000° F. They are not as accurate as are the rare-metal thermo-couples, but are more robust of construction, and cheaper. The rare-metal thermo-couples are formed, usually, by using one wire of platinum and one of 90 per cent. platinum and 10 per cent. rhodium. They may be used to measure temperatures as high as about 2,900° F.

666. The Temperature Of The Cold Junction Of A Thermo-electric Pyrometer Should Be Kept As Near Constant As Is Practicable.—Since (Sec. 175) the deflection of the instrument is proportional to the temperature difference between the hot and cold junctions, it is evident that if a temperature variation of the cold junction occurs, the temperature as indicated by the instrument will change, even though the actual temperature of the hot junction has remained constant. In installations where a high degree of accuracy is not required, the cold junction may be placed near the floor. A method of obtaining a more nearly constant cold-junction temperature is shown in Fig. 604. Various thermostatic devices are on the market which maintain the cold-junction temperature constant to within about 1° F. There are also other regulating devices called *compensators*, which, when connected into the circuit, so vary the circuit-resistance as to compensate for small cold-junction temperature variations.

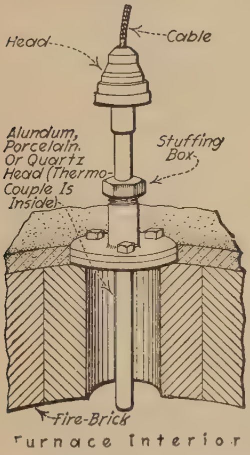


Fig. 603.—*Taylor Instrument Company's* short-type thermocouple.

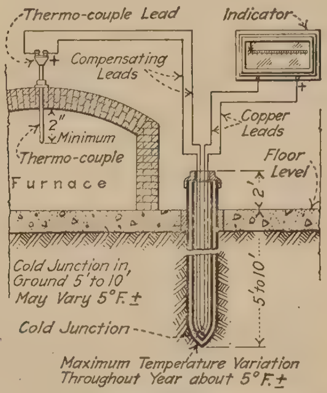


Fig. 604.—Installation showing method of burying cold junction of a thermo-electric pyrometer.

667. Calibration Of Thermo-electric Pyrometers may be readily effected by comparison with a standard gas thermometer. Such a calibration may be obtained from the Bureau Of Standards, Washington, D. C. A standardized pyrometer may be secured from any pyrometer manufacturer for use in plants where it is necessary that a large number of pyrometers be checked frequently. Chemically-pure salt (sodium chloride) which can be purchased at any chemical supply house, may be used for checking pyrometers. The salt is raised to a temperature of about 1,500° F., the thermo-couple inserted in the molten salt and the temperature allowed to drop. As the temperature decreases, there will be a temperature-drop lag when the salt freezes. At this point the pyrometer should read 1,474° F. The melting points of such metals as tin, zinc, and lead as given in Table 285 may also be used in calibrating pyrometers.

Note.—The Accuracy Of A Thermo-electric Pyrometer will depend upon: (1) *The precision of calibration.* (2) *The uncompensated temperature variation of the cold junction.* (3) *The scale graduations.* Temperatures may be determined by this instrument to within ±5° F. In general, thermo-electric pyrometers are accurate to within 0.5 per cent. of the temperature range of the instrument.

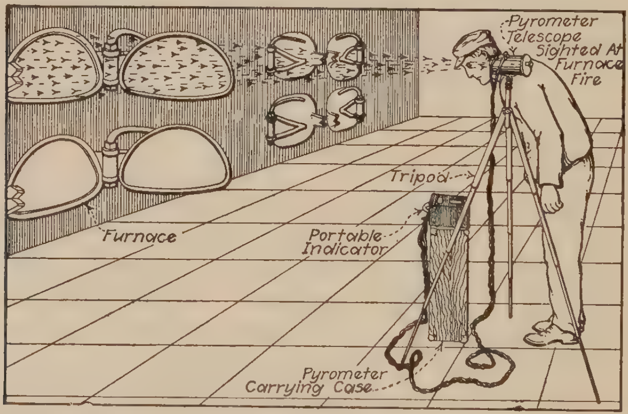


Fig. 605.—The Féry radiation pyrometer measuring temperature of inside of furnace.

668. The Féry Radiation Pyrometer (Fig. 605) utilizes the radiant energy (Sec. 142) which emanates from a hot object to measure the temperature of the object. It is particularly applicable as a portable instrument in determining high furnace temperatures (Fig. 606), and also the temperature of molten metals. An instrument of this type is not subject to any deterioration in measuring high temperatures because no part of the instrument will be heated to a temperature greater than about 280° F. This apparatus is capable of determining temperatures within an accuracy of about 5° F. from about 1,200 to 3,600° F. The calibration of the Féry radiation pyrometer is based upon the Stefan-Boltzmann law (Sec. 147) of black-body radiation. Therefore, unless the instrument is especially calibrated, certain correction coefficients must be applied to temperature readings taken upon bodies in the open, such as a stream of molten metal. These correction coefficients will be supplied by the manufacturer.

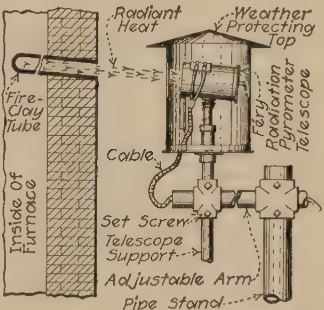


Fig. 606.—Outdoor installation of Féry radiation pyrometer, sighted into a fire-clay tube.

Note.—The Principle Of Operation Of The Féry Radiation Pyrometer may be explained thus; the instrument (Figs. 605 and 607) is sighted at the object, the temperature of which is to be determined, by looking through the eye-piece, *E*, (Fig. 607) and by focusing with the thumb-nut, *H*. The radiant heat waves are reflected by the concave mirror, *M*, and focused on the hot junction of a thermo-couple at *F*. The thermo-couple is connected to a voltmeter temperature indicator through the terminals, *T*. The temperature indicator may be either

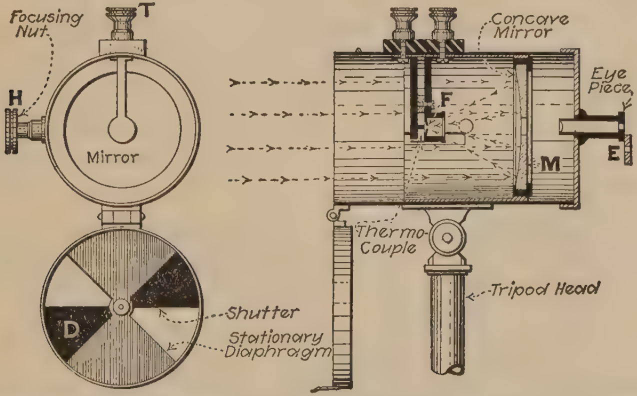


Fig. 607.—Elevation and section of the Féry radiation pyrometer telescope. (Based on design of *Taylor Instrument Co.*, Rochester, N. Y.)

of the indicating or recording type. A second scale is provided for higher temperatures. To use this second scale, the shutter, *D*, is partially closed over the mouth of the telescope, thereby decreasing the radiant energy which enters it. The instrument may be so designed that, within wide limits, its accuracy is independent of the size of the hot body or of the distance of the instrument from the body.

669. The Resistance Pyrometer is a temperature-measuring instrument—it may be either indicating or recording—which depends for its action upon the change in the electrical resistance of a conductor when the temperature of the conductor changes. These instruments are particularly well adapted for accurate temperature measurements over a range of from −150, or even lower, to + 1,800° F. They are accurate to within about 0.5 per cent., or within 2° at 400° F. In this instrument, a resistor coil of platinum, nickel alloy, or copper wire, which is enclosed within a suitable protecting tube, is installed at the point where the temperature is to be measured. Since the resistance of the resistor coil increases or decreases according to the temperature, this change in resistance can be readily and accurately measured with a Wheatstone bridge, a galvanometer, and a pair of dry cells.

NOTE.—THE CALIBRATION OF A RESISTANCE PYROMETER is usually effected by comparing its readings with those of a standard instrument, or by measuring its resistance in melting ice, in steam, and in the vapor of boiling sulphur; see also Sec. 667. Other temperatures are then calculated by means of formulas. The constants used in the formulas depend upon the *temperature coefficient of resistance* of the metal of the resistor coil.

670. Optical Pyrometers are temperature-measuring instruments which depend for their action upon the comparison of the intensity of the light which is emitted from the hot body, with the intensity of light which is emitted from a standard source—usually a standardized incandescent lamp. To minimize color difficulties, and to simplify the use of the instrument, only that wave length which to the eye appears red (Sec. 180) is retained. Then, by adjusting the apparatus so that two adjacent fields of vision, each of which is illuminated by one of the sources, have the same intensity of illumination, the temperature is determined by graduations on the instrument.

Note.—A Similar Instrument employs an incandescent lamp which is placed between the observer and the object, the temperature of which is to be measured. Then, with a rheostat, the current through the lamp is so adjusted that the lamp filament becomes invisible. A milliammeter is connected into the circuit to measure the lamp current and is graduated to read temperature in degrees. This type of instrument is comparatively inaccurate. Its use may be injurious to the operator's eyes. It cannot be employed for temperatures below 900° F.

671. Proper Installation And Maintenance Of Pyrometers Is Essential.—Only thus can satisfactory results be obtained. Stationary instruments should be mounted on a wall or post which is reasonably free from vibration. The thermo-couple or the resistance coil should be so installed in the furnace or heated device that the protecting tube extends at least 2 in. (Fig. 604) inside the wall. If a porcelain or fire-brick protecting tube is used, its temperature should, to lessen the probability of breakage, be raised slowly. A horizontally installed thermo-couple (Fig. 598) should not, where temperatures exceed about 1,600° F., extend into the furnace over 3 in. without being supported at the end. This is to prevent breakage due to sagging. All wiring should, where possible, be installed in conduit. Instruments should be checked frequently for accuracy. The indicating apparatus of pyrometers is extremely delicate, and should be handled accordingly.

672. Seger Cones, which have already been described in Sec. 283, are economical and satisfactory for estimating high temperatures in kilns and furnaces.

673. A Pressure Gage Is An Instrument For Measuring The Pressure (Fig. 16 and Secs. 5 to 19) exerted by a liquid, a vapor, or a gas. These instruments may, for various services be so designed and graduated as to read pressures which range from about 0.000 07 lb. per sq. in. in draft gages, up to about 5,000 lb. per sq. in. in hydraulic gages.

674. The Operation Of Pressure Gages Is Usually Based Upon One Of The Four Following Principles: (1) *The manometer*, Fig. 17. (2) *The Bourdon tube*, Fig. 608. (3) *The diaphragm*, Fig. 618. (4) *The spring-and-piston*, Fig. 624. Gages of any of these types may be employed to determine pressures which are either above or below that of the atmosphere. They are usually graduated to read in pounds per square inch, inches or millimeters of mercury column, or inches of water column. However, any other desired units of pressure (Sec. 19), such as ounces per square inch, pounds per square foot, and the like, may be used. Gages of each of the four above specified types are discussed in the following sections.

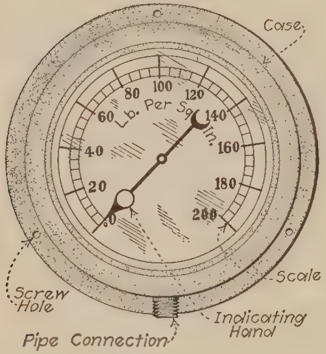


Fig. 608.—Bourdon-tube pressure gage.

675. The Manometer (Figs. 17 and 18) typifies the simplest form of pressure gage. It is particularly applicable for measuring partial vacuum, and (Fig. 609) low pressures such as those which are produced in the ashpit under a boiler where forced draft is used. Manometers are seldom employed to measure high pressures. This is because of the great length of tubing which would be required to obtain a practical working range. For principle of operation and description see Sec. 13. Manometer pressure gages of various designs are treated in the following sections.

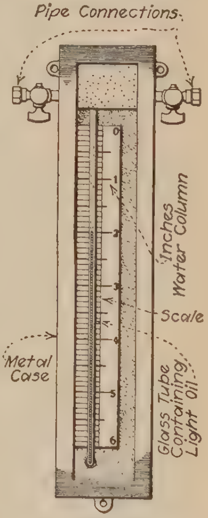


Fig. 609.—Manometer pressure gage for determining pressure of forced draft in ash pit.

Note.—Pressure Readings By Manometers Are Determined By The Difference In The Levels Of The Liquid In The Two Legs Of The Tube (Sec. 13). To obtain economical construction, a manometer (Fig. 610) which has one short leg, S, may be utilized. The cross-sectional area of S is many times larger than that of the long leg, L. Assume that the instrument is, when both tubes are open to the atmosphere, filled with mercury up to the 0-graduation mark. Now let the outlet, C, be connected to an exhaust pump and the air exhausted from L until the mercury has risen exactly 10-in. in L. Suppose the cross-sectional area of S is 10 times that of L. If the mercury rises 10 in. in L it will drop 1 in. in S. Hence, instead of the vacuum being 10 in. of mercury column it will be 11 in. Therefore, the distance from the 0-graduation mark to the 11-in. graduation mark must be 10 in. It follows that the distance between each successive 1-in. graduation must, if the instrument is to read directly in inches of mercury column, be 10/11 in. This method of construction is frequently employed in draft gages; see Fig. 611.

676. A Typical Draft Gage of the manometer type is shown in Fig. 611. By mounting the long leg, *L*, in an inclined position, increase or decrease in the vertical liquid-column height causes the liquid level (meniscus) to move along *L* a distance equal to (*the vertical distance moved*) × (*the cosecant of angle A*). This makes it possible to graduate the scale more closely. Thus, if the sine of the angle *A* is 0.1, its cosecant (reciprocal of the sine) is 10, and then a change in the impressed pressure of 1-in. water column will cause the liquid level to move 10 in. in *L*. Draft gages are usually graduated to 0.01 in. An oil (Red Seal, specific gravity, 0.83) which is lighter than water and which is colored red, is ordinarily used in these instruments. Thereby another means of scale lengthening is provided. The instrument must be adjusted by centering the bubble of the spirit level, *B*. Draft gages which are constructed for attachment of each end to a separate space and which indicate the *difference* of pressure in the two spaces, are called "*differential*" *draft gages*. For

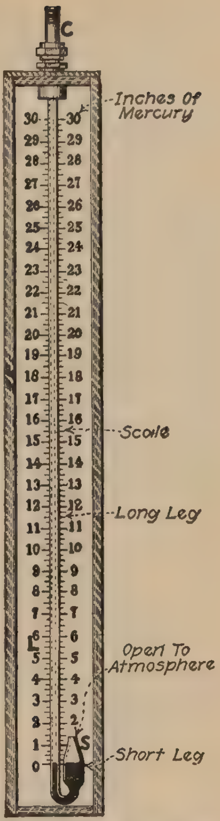


Fig. 610.—Short-leg manometer mercury vacuum gage.

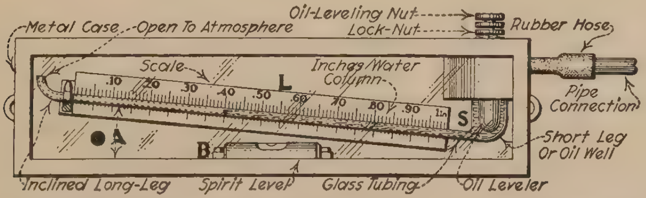


Fig. 611.—Typical draft gage of the manometer type. (*Defender Automatic Regulator Co., St. Louis, Mo.*)

detailed discussion concerning installation of draft gages, see the author's STEAM BOILERS and PRACTICAL BOILER ROOM ECONOMY.

NOTE.—THE BAROMETER, of both the manometer and diaphragm (aneroid) types, is discussed in Secs. 10 and 11.

677. The Bourdon-tube Pressure Gage (Fig. 608) is one which depends for its action on the change of curvature (Fig. 615) which occurs in a curved metallic tube when the pressure on a fluid therein is varied. A gage of this type is particularly applicable for measuring high pressures. It is also designed to measure pressures which are below that of the atmosphere. For determining pressures above atmospheric, these gages are usually graduated in pounds per square inch, but may also be graduated in feet of water column, tons per square inch, and in atmospheres. For measuring the pressures of partial vacuua (that is, pressures below atmospheric), they are generally graduated in inches of mercury column. A compound pressure gage (Fig. 612) is one which is designed to measure pressures both above and below atmospheric pressure on the same dial. Bourdon-tube pressure gages are suitable for measuring pressures as high as 50,000 lb. per sq. in. They are made both in the indicating and recording types. A recording pressure gage is similar in operation to the record-

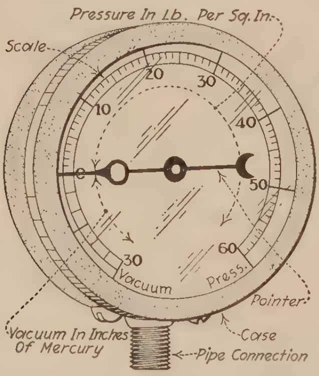


FIG. 612.—Combined pressure gage for measuring both pressure and vacuum with the same instrument.

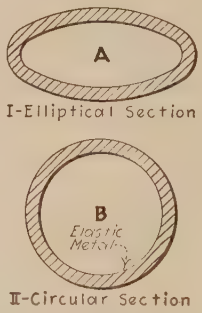


FIG. 613.—Elliptical and circular sections which have the same perimeter.

ing thermometer (Sec. 657). For explanation of Bourdon-tube-gage operation, see note below.

EXPLANATION.—THE PRINCIPLE OF THE BOURDON-TUBE PRESSURE GAGE is based on the fact that if a fluid is forced under pressure into a curved tube, the tube tends to straighten out. The straightening tendency is increased if the tube is of an oval section. Why this is true will be explained: If a fluid under sufficient pressure be forced into an elastic tube having an elliptical (or any other than a circular) section, A, (Fig. 613), the elastic tube will be forced to assume a circular section, B. Hence, it follows that if a fluid under pressure is forced into an elastic flat-tube ring (Fig. 614), when the ring section is changed by the internal pressure from a flattened circle, S_1 to a true circle S_2, the outer circumference of the tube will increase from C_1 to C_2. Likewise, the inner circumference will decrease from R_1 to R_2. Since the outer circumference is increased, the particles of the metal in it are under tension. Since the inner circumference is decreased, the particles in it are under compression.

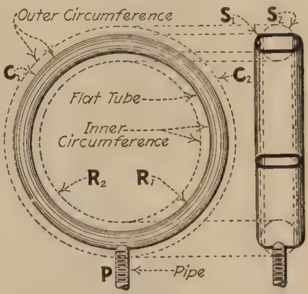


FIG. 614.—Showing how internal pressure in a flat flexible-tube ring changes shape of its cross-section, and thereby increases its external diameter and decreases its internal diameter.

Now, if pressure is applied to the interior of a flat curved tube (Fig. 615), the effect of the tension in the outer circumference and the compression in the inner circumference is to straighten the ring from the position shown by the dotted lines to the position shown by the full lines. The result is the same as that which would occur if tension were intro-

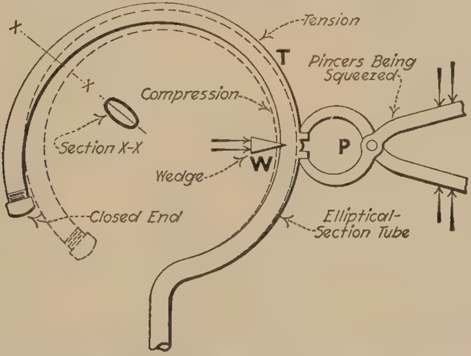


FIG. 615.—Illustrating principle of Bourdon tube. (Driving W into inner tube-wall produces compression therein. Pinching the outer tube-wall with P produces tension therein. Both operations tend to straighten the tube, T.)

duced at many points along the outer circumference by pinching parts of it together with pinchers (*P*, Fig. 615) and simultaneously introducing compression at many points in the inner circumference by driving therein wedges, *W*. In an actual Bourdon-tube gage (Fig. 616), the movement of the free end of the tube, *T*, as it tends to straighten, rotates the indicating hand, *I*. The motion is transmitted through the link, *L*, the sector, *S*, and the gear, *G*, which is mounted on the index-hand shaft.

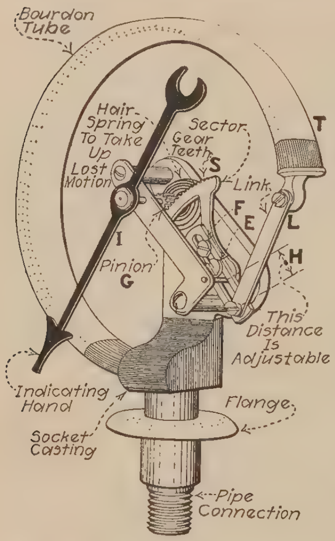
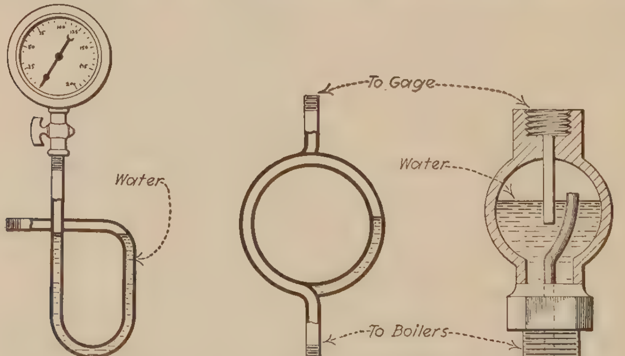


Fig. 616.—The mechanism of a Bourdon-tube pressure gage.

678. A Siphon Or Water-seal Must, For Steam-pressure Determinations With Bourdon-tube Gages, Be Interposed Between The Tube And The Steam (Fig. 617). The temperature of the Bourdon tube should not be permitted to exceed about 150° F. Temperatures greater than this in the tube may be prevented by a bent pipe or a vessel (Fig. 617 *I*, *II*, and *III*) which will always contain water. With such an arrangement there is a column of water between the hot steam and the gage tube. The gage tube contains relatively-cold water and a little air.



I-Goose-Neck Siphon II-Ring Siphon III-Simple Water-Seal

Fig. 617.—Typical gage siphons used with Bourdon-tube steam pressure gages.

NOTE.—BOURDON-TUBE GAGES FOR LOCATIONS WHERE THE WATER CONTAINED THEREIN MAY BE SUBJECTED TO FREEZING TEMPERATURES should be so made as to be self-draining.

679. The Diaphragm-type Pressure Gage is shown in Fig. 618. The general principle is the same as that of the aneroid barometer, Sec. 11. The corrugated diaphragm, *D*, is, when subjected to pressure, bulged upward or downward, depending the side on which the pressure is the greater. This movement is, transmitted through the connecting strut, *P*, the sector, *S*, and the gear, *G*, to the indication hand, *I*, thus moving *I* over the scale to indicate the pressure.

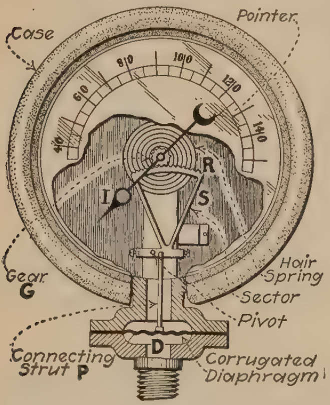


FIG. 618.—Illustrating principle of "diaphragm" pressure gage.

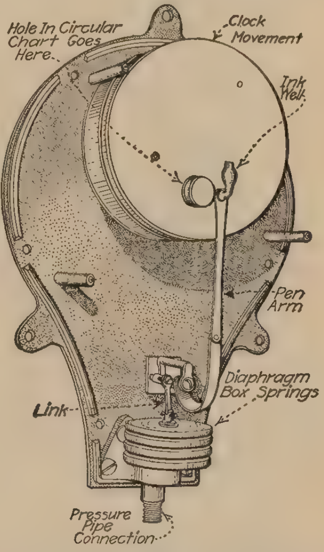


FIG. 619.—Multiple diaphragm or diaphragm-box-spring recording pressure gage—cover removed.

NOTE.—GAGES OF THE DIAPHRAGM TYPE ARE NOT SO WELL ADAPTED TO HIGH PRESSURES AS TO LOW PRESSURES.—Single-diaphragm gages similar to that of Fig. 618 are seldom, if ever, now manufactured, largely because the movement distance provided by a single diaphragm is insufficient for effective operation. For extreme sensitiveness in measuring low pressures, the usual practice is to arrange several thin-metal diaphragms (diaphragm box springs), Fig. 619, in series. These diaphragm box springs are similar to that shown in the radiator trap, Fig. 522. Pressures which are either above or below atmospheric may be measured with instruments of this type. Both indicating and recording diaphragm pressure gages are on the market.

680. The Calibration Of Gages may be effected by comparison with a so-called *test-gage*. Test-gages generally have finer graduations than ordinary gages and are also more carefully made and adjusted. The comparison between the test gage and the service gage can be made by connecting both to the same piping system in which the pressure can be varied. Test-gages should be calibrated from time to time with some standard source. A vacuum gage may be calibrated by the method shown in Fig. 620.

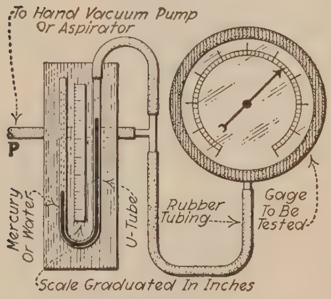


Fig. 620.

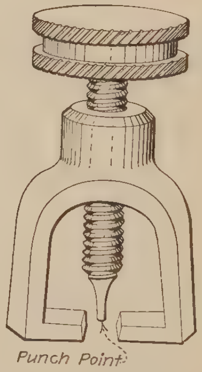


Fig. 621.

Fig. 620.—Apparatus for calibrating a vacuum gage. (Non-collapsible tubing must be employed for all connections. By connecting P to a pressure pump, the apparatus may also be used for calibrating low-reading pressure gages.)

Fig. 621.—Gage-hand jack.

Note.—To Adjust An Error In A Gage Of The Dial Type, the indicating hand should, if the error is constant throughout the scale, be removed with a *gage-hand jack* (Fig. 621)—a tool which will be supplied for this purpose by any gage manufacturer. Then the hand may be accurately reset. A Bourdon-tube gage may be accurate on its scale at, say, 50 lb. per sq. in. and inaccurate on its scale at 150 lb. per sq. in. When this condition exists, the adjustment is made by loosening the screws, E and F (Fig. 616), and changing the distance H. If H is decreased, the movement of the indicating hand is increased. Therefore, if the gage reads low on its scale at 150 lb. per sq. in., H should be decreased, and vice versa.

681. A Dead-weight Gage Tester (Fig. 622) provides an absolute standard for gage calibration. Boiler inspectors usually employ such an instrument as a primary standard for gage testing.

EXPLANATION.—A DEAD-WEIGHT GAGE TESTER (Fig. 622) has a platform, *T*, secured to a piston, *P*. The piston is accurately fitted into a cylinder *C*, which when new, has a cross-sectional area of 0.2 sq. in. This cylinder communicates at its lower end to a reservoir, *R*, which is fitted with a piston, *S*, and which is moved in or out by a screw that is operated by a handwheel, *H*. A pipe, *Q*, which connects to the lower part of *R*, is provided with unions and fittings for attaching the gage, *G*, that is to be tested.

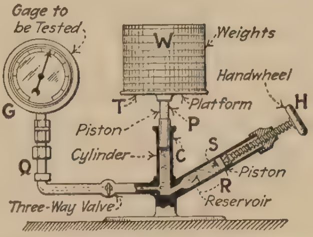


FIG. 622.—Section of a dead-weight gage tester.

To operate the device, the three-way valve is closed and *S* is screwed down to the bottom of *R*. Then *P* is removed and *C* filled with clean oil. By screwing *S* upward, the oil is drawn into *R*. No air should be permitted to entrap in *R*. Attach the gage, *G*, which is to be tested. Open the three-way valve. Add weights *W* to produce the desired pressure in *G*. (Since the area of *P* is 0.2 sq. in., each 1 lb. added to the platform will produce a pressure of: 1 ÷ 0.2 = 5 *lb. per sq. in* on the oil, which is transmitted thereby to the gage. The weight of the platform and plunger—usually 1 lb.—must always be included in the weight which produces the pressure.) As the weights, *W*, are placed on the platform, *S* must, to keep *T* floating, be screwed down. When observations are being taken, the platform should, to reduce the effect of piston-and-cylinder friction to a minimum, be given a slight rotary motion with the hand. When *G* has been tested, screw *H* outwardly to the limit. Close the three-way valve. Remove *G*. The tester is now ready for the next test.

682. Concerning The Accuracy Of Gages, definite values cannot be given. Primarily, the accuracy of a gage depends upon the precision of calibration, which, in turn, will be governed by the scale graduations. It is obvious that a draft gage can be calibrated and read more nearly accurate than can a high-pressure hydraulic gage. A gage of the dial type should be accurate to within an amount equal to about 1.5 times the width of that portion of the indicating hand which lies above the gage scale, measured to the scale of the gage.

EXAMPLE.—If the width of a pressure-gage hand end covers 2 lb. per sq. in. on the scale, then the gage should be accurate to within: 1.5 × 2 = 3 *lb. per sq. in.*

683. "Combination" Graduations For Pressure Gages are often useful. Thus, a gage may be scaled both in *feet of water* *column* and in *pounds per square inch*. When so scaled, the gage may be used to read simultaneously the height of water in a stand-pipe and the pressure in pounds per square inch which is produced by the water column. Similarly, a steam-pressure gage may be graduated to read both the pressure of the steam in pounds per square inch and the temperature of the saturated steam (see Sec. 394). This arrangement is similar in function to that of the temperature-pressure thermometer of Fig. 593.

684. An Engine Indicator (Figs. 623 and 624) may be considered as a recording pressure gage which draws a graphic record of the pressures which exist within an engine cylinder during one cycle (Sec. 402 defining cycle). The pressure variation throughout a stroke, as recorded by a pencil line (*Q*, Fig. 623) on a piece of paper by an indicator, is called an *indicator diagram*. For further discussion of indicators and indicator diagrams and their applications, see the author's Steam-engine Principles And Practice.

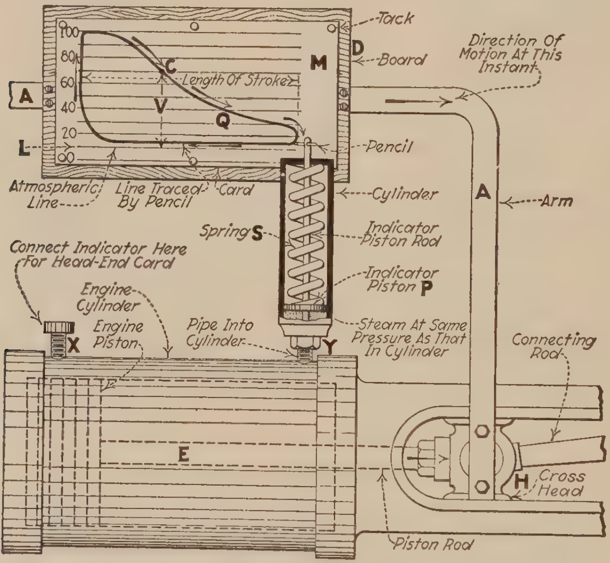


Fig. 623.—Elementary indicator for obtaining a pressure-position diagram for crank end of engine cylinder. (To take diagram for head-end, indicator is connected to *X*, then *D* is shifted the proper distance to the left along *A* and there resecured.)

Explanation.—As the engine crosshead (H, Fig. 623) moves, it carries with it the arm, A, which supports board, D. On D is tacked a card, M. Simultaneously, as the pressure within cylinder, E, varies, the indicator piston, P, moves up or down. The pencil (fixed to P) records the movement on M. The spring, S, which restrains the pressure against P, is so made that a certain pressure against P will cause a desired length of vertical movement. It follows that the indicator diagram, Q, traced in Fig. 623 by the pencil on the card, will be a graphic record of the variation in pressure, in that portion of the cylinder which is on the right of the engine piston, at the different instants during its stroke.

The vertical distance, V, of any point, C, on Q, from a line, L, (which represents the atmospheric pressure and which is drawn when only the pressure of the atmosphere is on both sides of P) is proportional to the pressure above or below atmospheric, in the crank end of E at that point in the stroke.

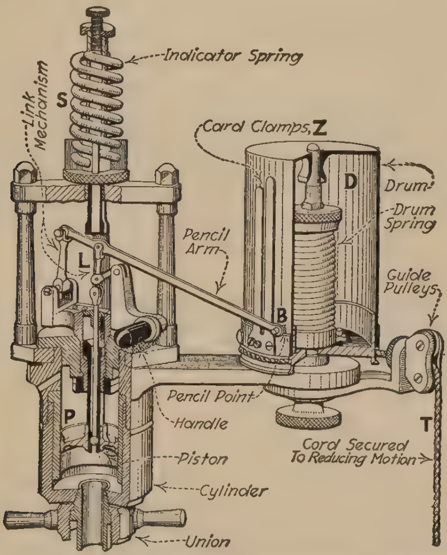


Fig. 624.—Semi-sectional view of *Crosby* "outside-spring" steam-engine indicator.

685. An Actual Steam-engine Indicator (Fig. 624) embodies refinements not incorporated in that of Fig. 623. The general principle is, however, the same for both. Where feasible, the same reference letters have been used on both illustrations.

Explanation.—The cord, T (Fig. 624), is indirectly attached to the engine crosshead. The blank-indicator card is held around D by the clamps, Z. A *reducing motion*, which may be of any one of several designs (see *R*, Fig. 625 for an example) is interposed between the crosshead and the indicator so that the circular travel of the drum, *D* (Fig. 624) will not be excessive and will be proportional to the travel of the engine piston. The link mechanism, *L*, must be so designed that *B* will travel only in a straight vertical line. Different accurately calibrated springs, *S*, are used for different maximum steam pressures under which engines may have to be tested.

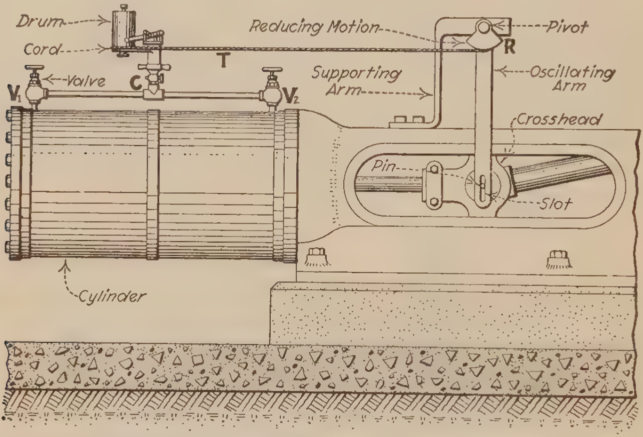
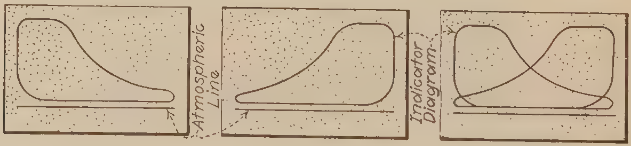


Fig. 625.—Indicator arranged for taking diagrams on a double-acting steam engine. (A three-way valve inserted at *C*, provides greater accuracy than do valves V_1 and V_2.)

Note.—In Taking Steam Engine Indicator Diagrams (Fig. 625) a diagram is first taken for one "end" (Fig. 626-*I*) of the cylinder. Then by closing V_1 and opening V_2, a diagram is taken for the other end as shown at *II*. Usually in practice both diagrams are taken on the same card as shown at *III*.



I-Head End II-Crank End III-Combined

Fig. 626.—Indicator diagrams.

686. A Hygrometer is an instrument which is employed for determining the moisture content—humidity (Sec. 333)—of air. Most hygrometers depend for their operation on the wet-and-dry-bulb-thermometer principle (Sec. 334). The sling psychrometer (Fig. 322) is probably the most accurate of the various humidity-determining instruments. To insure dependable results, the velocity of the air which surrounds the bulbs of any wet-and-dry-bulb hygrometer should equal or exceed about 800 ft. per min. A stationary hygrometer is shown in Fig. 627; the objection to this instrument is that, due to irregular air circulation over the bulbs, erroneous readings are likely to result.

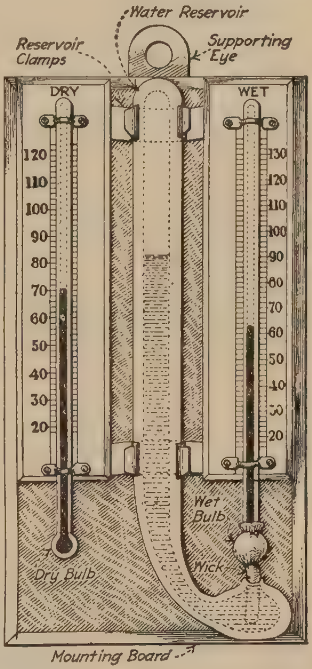


Fig. 627.—Stationary hygrometer.

Note.—Relative-humidity Determinations Made With A Stationary Wet-bulb Hygrometer In Still Air Will Usually Be Erroneous.—The following is adopted from a statement by the Taylor Instrument Co., Rochester, N. Y.: "If the relative humidity to be measured is in the neighborhood of 20 per cent. or less, and the air temperature is between 40 and 45° F., then there will be, for the same temperature condition, a difference in the relative-humidity reading of approximately 30 per cent. between air absolutely still and air in motion at 800 ft. per min. If the humidity is between 75 and 80 per cent. and the temperature between 85 and 100° F., then there will be practically no difference between the humidity reading obtained in still air and in air in motion at 800 ft. per min. If the air is in motion, subject to the ordinary drafts that may be present in rooms, then the error under such conditions as compared with the readings with an air velocity of 800 ft. per min. will be somewhere between the limits given above." To obtain accurate results with the relative-humidity tables (Table 335) as published by the U. S. Weather Bureau, an air velocity of about 800 or 900 ft. per min. should (so the Weather Bureau advises) prevail. No appreciable difference in the relative-humidity value will result, however, if the air velocity is as low as 600 ft. per min.

687. A Recording Hygrometer Or Recording Wet-and-dry-bulb Thermometer, the operation of which is similar to that of the recording thermometer (Sec. 657) is shown in Fig. 628. This instrument is equipped with a moter-driven fan which, when in operation, produces a continuous and constant air circulation over the bulbs. Where the wet and dry bulbs can be mounted in a duct (Fig. 629) in which the velocity of the air exceeds about 800 ft. per min., then the blower is unnecessary.

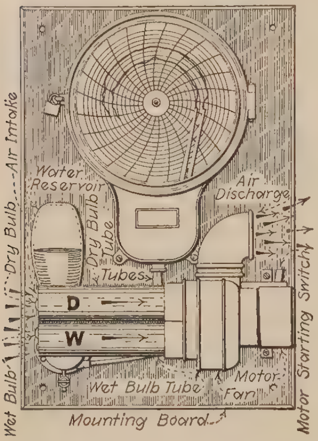


Fig. 628.—Wet- and dry-bulb recording thermometers, provided with fan-driven motor. (*Taylor Instrument Co.*)

Note.—A Type Of Hygrometer Called A Hygrodeik is shown in Fig. 630. It is practically self-reading, inasmuch as the humidity table is mounted on the instrument in the form of a chart. To read the instrument, the index hand, *I*, is swung to the left-hand scale, *L*, and the sliding pointer, *P*, set to the degree line upon this scale which corresponds to the wet-bulb temperature as indicated by the wet-bulb thermometer on *L*. Then *I* is swung to the right until *P* intersects the curved line which extends downward to the left from the degree point on *R* corresponding to the indicated dry-bulb temperature. The index hand will then be pointing to the relative humidity, *H*, at the bottom of the chart. The dew point and also the absolute humidity may be determined directly from the chart. This instrument is

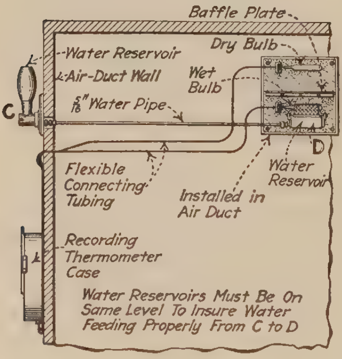

Baffle Plate
Water Reservoir
Air-Duct Wall
Dry Bulb
Wet Bulb
⅜" Water Pipe
C
D
Flexible Connecting Tubing
Water Reservoir
Installed in Air Duct
Recording Thermometer Case
Water Reservoirs Must Be On Same Level To Insure Water Feeding Properly From C to D

Fig. 629.

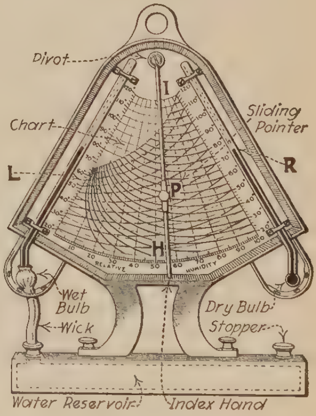


Fig. 630.

Fig. 629.—Typical installation of remote-reading recording thermometers for determining humidity in an air duct. (*Taylor Instrument Co.*)
Fig. 630.—A hygrodeik.

subject to the same inaccuracies as is the stationary hygrometer of Fig. 627.

688. Table Showing Approximate Costs Of Various Instruments.—(These data, which were compiled from manufacturers' catalogs, are not intended to present definite prices, but merely to give the reader an idea of the relative costs.)

Instrument	Type		Price range, in dollars
THERMOMETERS	Bulb and stem mounted on wood or metal		0.25 to 4
	Same as above, with bulb located in separable socket threaded for pipe tap		3 to 45
	Engraved		2 to 37
	Remote-reading		75 to 150
PYROMETERS	Thermo-electric	Indicating	60 to 175
		Recording	175 to 600
	Radiation, indicating		175 to 470
	Resistance, indicating		100 to 200
	Seger cones		0.05
PRESSURE GAGES	Draft gages	Manometer	14 to 35
		Diaphragm	60 to 80
	Bourdon tube	Hydraulic	22 to 70
		Steam	4 to 35
INDICATORS	Steam engine		100 to 275
HYGROMETERS	Sling psychrometer		4 to 10
	Stationary W-. and D-. bulb		5 to 40
	Distance, recording		150 to 250

689. Table Showing Ranges And Accuracy Of Different Temperature-measuring Instruments, thermometers, pyrometers, Segar cones and the like. From Moyer, J. A. "Power Plant Testing."

Devices			Range, degrees Fahrenheit	Probable accuracy, degrees Fahrenheit
Type	Class			
THERMOMETERS	Mercury	Ordinary type	− 38 to + 575	From 1° in common instruments up to 0.01°.
		Jena glass, capillary tube filled with nitrogen.*	− 38 to +1,000	Higher ranges accurate to 1°.
		Quartz glass, capillary tube filled with nitrogen.	− 37 to +1,500	Higher ranges accurate to 1°.
		Alcohol or petrol ether	− 325 to + 100	Accurate to 1°.
PYROMETERS		Electrical resistance, "bridge" and galvanometer.	− 400 to +2,200	Accurate to 0.01° for range 0° to 500°.
		Thermo electric	− 400 to +3,000	Reliable to nearest 5°.
		Metallic (mechanical)	+ 300 to +1,000	Uncertain.
		Vapor (usually recording)	+ 95 to +1,350	Reliable to nearest 2° to 10°.
	Radiation	Thermo-couple in focus of mirror (Féry).	+ 300 to +4,000	Reliable to about nearest 20°.
		Bolometer	− 400 to sun	Reliable to about nearest 20°.
		Optical	+1,000 to sun	Reliable to about nearest 20°.
		Seger pyrometer cones	+1,100 to +3,600	Reliable to about nearest 20°.

Note.—*Mercury boils at a temperature of 675° F. In the common mercurial thermometer there is a vacuum in the capillary tube above the mercury and the pressure at any point in the temperature range is that of the mercury vapor alone. Consequently such thermometers cannot be used where the temperatures exceed 675° and they are unreliable when that temperature is approached. To obviate this difficulty, the capillary tubes are sometimes filled with nitrogen, or some other inert gas that will not attack the mercury, under high pressure. As the mercury expands against the gas, the pressure upon the mercury is increased and the boiling point is raised.

QUESTIONS ON DIVISION 19

1. Name some heat effects which can be measured.
2. What is a thermometer? How may thermometers be classified?

3. What two liquids are frequently employed in thermometers as the expansion medium?

4. What kind of a thermometer should be used for accurate temperature determinations?

5. Explain by sketch, the operation of a bi-metallic thermometer.

6. What is a *remote-reading* thermometer? Why is their use sometimes necessary?

7. What is a *recording* thermometer?

8. Explain the operation of a mercury recording thermometer.

9. How are thermometers usually calibrated?

10. What precautions should be observed in the use of thermometers?

11. What is a *pyrometer?* Why must a pyrometer be used to measure high temperatures?

12. Name five principal types of pyrometers.

13. Explain the operation of a thermo-electric pyrometer.

14. Why should the cold-junction temperature of such an instrument be maintained nearly constant? What methods are frequently employed to obtain a nearly constant cold-junction temperature?

15. How may thermo-electric pyrometers be calibrated? Upon what factors does the accuracy depend?

16. To what service is a Féry radiation pyrometer particularly applicable?

17. Explain the operation of a resistance pyrometer.

18. What are the disadvantages of an optical pyrometer?

19. What is a *pressure gage?*

20. Name four principles of pressure-gage operation.

21. Why are draft gages frequently made with one short leg and one long inclined leg? Why is oil often used in draft gages instead of water?

22. Explain, with sketches, the principle of the Bourdon tube.

23. To what applications are Bourdon-type gages suitable?

24. Why must a siphon be used in connection with Bourdon-tube steam gages?

25. What are the services to which a diaphragm pressure gage may be adapted?

26. Explain two methods of calibrating gages.

27. Name the units in which gages may be graduated.

28. What is an engine indicator? Explain its operation.

29. What is a hygrometer?

30. Name and explain two types of hygrometers.

APPENDIX

SOLUTIONS TO PROBLEMS

SOLUTIONS TO PROBLEMS ON DIVISION 1

FORCE, PRESSURE, WORK, ENERGY, POWER

1. Since 1 ton $= 2{,}000$ lb., the *force* required $= 1 \times 2{,}000 = 2{,}000$ *lb.*

2. Yes. A force of 5 lb. between the wrench and the floor.

3. By For. (1), $P = \frac{W}{A} = \frac{20{,}000}{50} = 400$ *lb. per sq. ft.*

4. By For. (4), $P_A = P_G + 14.7 = 128 + 14.7 = 142.7$ *lb. per sq. in.*

5. By For. (5), $P = 0.4912 \times 28.5 = 13.999$ *lb. per sq. in.*

6. The *height of water column* $= 30 \times 12 = 360$ *in.* By For. (7) $P_M = 0.073{,}55\, P_I = 0.073{,}55 \times 360 = 26.48$ *in.*

7. 12 *lb.* A force cannot act and the system remain in equilibrium without being opposed by another force which has the same magnitude.

8. By solution of example subjoined to Sec. 3, the *drawbar pull* $= \frac{(100{,}000 \times 5)}{100} = 5{,}000$ *lb.*

9. By For. (13), $W = FL = 50 \times 15 = 750$ *ft.-lb.*

10. By For. (13), $W = FL = 35{,}000 \times \frac{1}{2} = 17{,}500$ *in.-lb.*

11. By For. (15), $\mathrm{P} = \frac{FL}{33{,}000t} = \frac{(140 - 65) \times 300}{33{,}000 \times 1} = 0.68$ *hp.*

12. The *piston travel* $= (15 \div 12) \times 90 = 112.5$ *ft. per min.* By For. (15), $\mathrm{P} = \frac{FL}{33{,}000t} = \frac{(3{,}500 \times 112.5)}{33{,}000 \times 1} = 11.9$ *hp.*

13. The *weight of the water delivered* $= 1{,}500 \times 8.3 = 12{,}450$ *lb. per min.* By For. (13), foot-pounds $= W = FL$. $\mathrm{P} = \frac{FL}{t} = 12{,}450 \times 350 = 4{,}357{,}500$ *ft.-lb.* done in one minute. By For. (15), $\mathrm{P} = \frac{FL}{33{,}000t} = \frac{(4{,}357{,}500)}{33{,}000 \times 1} = 132$ *hp.*

14. The *time* $= 3 \times 60 = 180$ min. By transposition of For. (15) the *weight of water pumped* $= F = \frac{33{,}000t\mathrm{P}}{L} = \frac{33{,}000 \times 180 \times 6}{75} = 475{,}200$ lb. or $475{,}200 \div 8.3 = 5{,}725.3$ *gal.*

SOLUTIONS TO PROBLEMS ON DIVISION 2

MATTER, HEAT, TEMPERATURE

1. By For. (19), $T_F = \frac{9}{5}T_C + 32 = [\frac{9}{5} \times 357] + 32 = 674.6°$ **F.**

2. By For. (19), $T_F = \frac{9}{5}T_C + 32 = [\frac{9}{5} \times (-75.5)] + 32 = -103.9°\ F.$

3. By For. (18), $T_C = \frac{5}{9}(T_F - 32) = \frac{5}{9} \times (2{,}750 - 32) = 1{,}510°$ C.

4. By For. (18), $T_C = \frac{5}{9}\ (T_F - 32) = \frac{5}{9} \times (-396.4 - 32) = -238°\ C.$

5. By For. (20), $\mathrm{T}_F = T_F + 460 = 212 + 460 = 672°$ F. *abs.* $\mathrm{T}_F = T_F + 460 = 460 + 460 = 920°$ *F. abs.* $\mathrm{T}_F = T_F + 460 = -32 + 460 = 428°$ *F. abs.*

6. By For. (21), $\mathrm{T}_C = T_C + 273 = 100 + 273 = 373°$ *C. abs.* $\mathrm{T}_C = T_C + 273 = 0 + 273 = 273°$ *C. abs.* $\mathrm{T}_C = T_C + 273 = -175 + 273 = 98°$ *C. abs.* $\mathrm{T}_C = T_C + 273 = 20 + 273 = 293°$ *C. abs.*

SOLUTIONS TO PROBLEMS ON DIVISION 4

HEAT—ITS MEASUREMENT AND TRANSFORMATIONS

1. By For. (22), $Q = W(T_2 - T_1) = 35(212 - 55) = 5{,}495$ *B.t.u.*

2. By For. (22), $Q = W(T_2 - T_1) = 265 = 8(T_2 - 60)$. Solving for T_2: $T_2 = (265 \div 8) + 60 = 93.13°$ F.

3. *Heat applied to water* = 0.50 × 50,000 = 25,000 *B.t.u.* By For. (22), $Q = W(T_2 - T_1) = 25{,}000 = W \times (210 - 65)$. Solving for W: $W = 25{,}000 \div (212 - 65) = 172.4$ *lb.*

4. *Large calories given off* = *kilograms* × *deg. cent.* = 15 × 35 = 525 *large calories.* By For. (26), 525 large calories = 525 × 3.968 = 2,084 *B.t.u.*

5. At 14,000 B.t.u. per lb., 17 lb. of coal represent 17 × 14,000 = 238,000 *B.t.u.* The energy delivered as available work = 0.12 × 238,000 = 28,560 *B.t.u. per hour.* By For. (30), the horsepower = 28,560 ÷ 2,545 = 11.22 *hp.*

6. By For. (31), $C = \dfrac{Q}{W(T_2 - T_1)} = \dfrac{8.75}{4.5 \times (83 - 65)} = 0.108.$

7. By For. (32), $Q = CW\ (T_2 - T_1) = 0.115 \times 75 \times (1{,}500 - 80) = 12{,}245$ *B.t.u.*

8. By For. (32), $Q = CW(T_2 - T_1) = 0.119 \times 125 \times (180 - 40) = 2{,}082$ *B.t.u.* By For. (27), 2,082 *B.t.u.* is equivalent to 2,082 × 778 = 1,620,000 *ft.-lb.*

9. By For. (32), $Q = CW(T_2 - T_1) = 0.24 \times 30 \times (565 - 65) = 3{,}600$ *B.t.u.*

10. By For. (38), $T = \dfrac{W_1C_1T_1 + W_2C_2T_2}{W_1C_1 + W_2C_2} =$

$$\frac{(6 \times 0.119 \times 2{,}300) + (5 \times 8.3 \times 1 \times 50)}{(6 \times 0.119) + (5 \times 8.3 \times 1)} = 88°\ \text{F.}$$

11. By For. (38), $T = \dfrac{W_1C_1T_1 + W_2C_2T_2}{W_1C_1 + W_2C_2}$

$$= \frac{(16 \times 1 \times 40) + (10 \times 1 \times 110)}{(16 \times 1) + (10 \times 1)} = 66.9°\ F.$$

12. By For. (33), $C_H = \dfrac{C_CW_C(T_M - T_C)}{W_H(T_H - T_M)} = \dfrac{1 \times 8 \times (60 - 35)}{12 \times (212 - 60)}$

$= 0.109{,}6 =$ *specific heat.*

13. By For. (44): $W_V = 778Q_V = 778 \times 5{,}495 = 4{,}275{,}110$ *ft.-lb.*

14. By For. (45): $W_D = 778Q_D = 778 \times 10.5 = 8{,}170$ *ft.-lb.*

15. By For. (48): $W_E = P \times (V_2 - V_1) = (100 \times 144) \times (4.429 - 0.0177) = 63{,}550$ *ft.-lb.*

16. By For. (46) and Prob. 15: $Q_E = W_E/778 = 63{,}550 \div 778 = 81.7$ *B.t.u.* Also, by For. (56): $Q_L = Q_D + Q_E = 806.6 + 81.7 = 888.3$ *B.t.u.*

17. By For. (22): $Q_V = W(T_2 - T_1) = 1 \times (327.8 - 32) = 295.8$ *B.t.u.*

18. By For. (57): $Q_I = Q_V + Q_D = 295.8 + 806.6 = 1{,}102.4$ *B.t.u.*

19. By For. (58): $Q = Q_I + Q_E = 1{,}102.4 + 81.7 = 1{,}184.1$ *B.t.u.*

SOLUTIONS TO PROBLEMS ON DIVISION 5

TRANSFER OF HEAT

1. *Rate of heat conduction* $= 41 \times \dfrac{6.5}{5} = 53.3$ *B.t.u. per min.*

2. *Thermal pressure* $= 500 - 100 = 400°$ *F.*

3. By For. (62), the *thermal conductance* $= B = \dfrac{Q}{t(T_2 - T_1)} =$

$$\frac{700}{5 \times (300 - 70)} = 0.609 \textit{ mohts.}$$

4. By For. (63), the *thermal pressure* $= (T_2 - T_1) = \dfrac{Q}{t\,B} =$

$$\frac{8{,}720}{(1.167 \times 11)} = 679.3° \textit{ F.}$$

5. By Table 125, the value of K_S per square-foot-inch for steel = 320. By For. (66), *the thermal conductance* $= B = \dfrac{K_S A}{L} = \dfrac{(320 \times 30)}{0.5} =$ 19,200 *mohts.*

6. The *circumference* of a 6-in. pipe = 3.14 × 0.5 = 1.57 *ft.* The *area of the covering* = (20 × 1.57) = 31.4 *sq. ft.* By Table 125, the value of K_S, per square-foot-inch, for mineral wool = 0.42. By For. (71), $Q = \dfrac{K_S A(T_2 - T_1)t}{L} = \dfrac{0.42 \times 31.4 \times (300 - 90) \times 10}{4} = 6{,}923$ *B.t.u.*

7. By For. (78), the *heat-flow* $= Q = \dfrac{(T_2 - T_1)t}{R} = \dfrac{(1{,}500 - 310) \times 5}{0.000{,}267{,}2}$ $= 22{,}267{,}964$ *B.t.u.*

8. By Table 125, the value of K_S, per square-foot-inch, for brickwork = 3.40. By For. (66), the *thermal conductance through each square foot of the well-area* $= \dfrac{K_S A}{L} = \dfrac{(3.40 \times 1)}{9} = 0.378$ *moht.* By Sec. 129, the *thermal resistance* $= \dfrac{1}{0.378} = 2.65$ *thoms per sq. ft.*

9. The *area of the wall* = 6 × 15 = 90 *sq. ft.* By Table 125, the value of K_S, per square-foot-inch, for brickwork = 3.4. By For. (66), the *thermal conductance through the wall* = $\frac{K_S A}{L} = \frac{3.4 \times 90}{15} = 20.4$ *mohts*. By Sec. 129, the *thermal resistance* = $\frac{1}{20.4} = 0.049$ *thoms*. By For. (79), the *heat-power loss* = $\frac{T_2 - T_1}{\mathrm{R}} = \frac{2{,}000 - 190}{0.049} = 36{,}938$ *B.t.u. per hr.*

10. By Table 149, k, for wrought-iron bodies = 0.154. By For. (83) the *heat radiated under the initial fire-temperature* = $\mathrm{Q}_R = k\left[\left(\frac{\mathrm{T}_1}{100}\right)^4 - \left(\frac{\mathrm{T}_2}{100}\right)^4\right] = 0.154\left[\left(\frac{2{,}400 + 460}{100}\right)^4 - \left(\frac{700 + 460}{100}\right)^4\right] = 100{,}250$ *B.t.u. per hr. per sq. ft. of hot fuel bed area.* By For. (83), the *heat radiated under the increased fire-temperature* = $\mathrm{Q}_R = k\left[\left(\frac{\mathrm{T}_1}{100}\right)^4 - \left(\frac{\mathrm{T}_2}{100}\right)^4\right] = 0.154\left[\left(\frac{2{,}600 + 460}{100}\right)^4 - \left(\frac{700 + 460}{100}\right)^4\right] = 132{,}250$ *B.t.u. per hr. per sq. ft. of hot fuel bed area. Increase of radiated heat* = 132,250 − 100,250 = 32,000 *B.t.u. per hr. per sq. ft. of hot fuel bed area.*

SOLUTIONS TO PROBLEMS OF DIVISION 7

EXPANSION AND CONTRACTION OF SOLIDS AND LIQUIDS

1. By For. (97): $L_2 = L_1 + L_1 e_L (T_2 - T_1) = 26.1 + [26.1 \times 0.000{,}010{,}7(212 - 40)] = 26.148$ *in.* Pointer will move: $(10 \div 1) \times 0.048 = 0.48$ *in.*

2. Substituting in For. (94): $l = e_L L_1 T = 0.000{,}005 \times 26.1 \times 172 = 0.022$ *in.*

3. *Difference in temperature* = 110 − (−30) = 110 + 30 = 140° *F*. By For. (94): $l = e_L L_1 T = 0.000{,}006{,}3 \times (98 \times 12) \times 140 = 1.04$ *in.*

4. Substituting in For. (94): $l = e_L L_1 T = 0.000{,}006{,}3 \times (50 \times 12) \times 1 = 0.003{,}78$ *in.* To bend or shift the piers.

5. Substituting in For. (94): $X = l = e_L L_1 T = 0.000{,}006{,}3 \times 300 \times (300 - 50) = 0.473$ *ft.* or about 5.7 *in.*

6. Substituting in For. (94): *expansion* $l = e_L L_1 T = 0.000{,}008 \times (100 \times 12) \times 100 = 0.96$ *in. Width of expansion joint* = $5l = 5 \times 0.96 = 4.8$ *in.* By For. (99): *Increase in area* = $A = e_S A_1 T = 2 e_L A_1 T = 2 \times 0.000{,}008 \times (30 \times 100) \times 100 = 4.8$ *sq. ft.*

7. Transposing For. (102) and substituting: *stress* = $E \times$ *strain* = $28{,}000{,}000 \times (0.0001 \div 12) = 233.3$ *lb. per sq in.*

8. By For. (102): $E = \frac{\mathit{stress}}{\mathit{strain}} = (1{,}500 \div 0.3) \div (0.002 \div 10) = 5{,}000 \div 0.000{,}2 = 25{,}000{,}000$ lb. per sq. in.

9. Transposing For. (102) and substituting: *strain* = *stress* $\div E = (200{,}000 \div 12) \div 30{,}000{,}000 = 0.000{,}55$ *in. per inch*, on a total for 16 in. $= 16 \times 0.000{,}55 = 0.008{,}8$ *in.*

10. By For. (94): $l = e_L L_1 T = 0.000{,}006{,}3 \times (375 \times 12) \times 350 = 9.92$ *in.* By For. (107): $F = E e_L T A = 30{,}000{,}000 \times 0.000{,}006{,}3 \times 350 \times 2.5 = 165{,}375$ *lb.*

11. By For. (94): $l = e_L L_1 T = 0.000{,}006{,}3 \times (20 \times 12) \times (600 - 50) = 0.83$ *in.* By For. (106): *Stress* $= E e_L T = 30{,}000{,}000 \times 0.000{,}006{,}3 \times 400 = 75{,}600$ *lb. per sq. in.*

12. By For. (101), the *final volume,* $V_2 = V_1(1 + e_V T) = 500\{1 + [0.000{,}1 \times (210 - 50)]\} = 500\ (1 + 0.016{,}0) = 500 \times 1.016 = 508$ *gal.* or an increase of $508 - 500 = 8$ *gal.*

SOLUTIONS TO PROBLEMS ON DIVISION 8

HEAT PHENOMENA OF GASES

1. By For. (109), $P_2 = \dfrac{P_1 V_1}{V_2} = \dfrac{14.7 \times 12.39}{2} = 91.07$ *lb. per sq. in. abs.* or, 76.37 *lb. per sq. in. in gage.*

2. By For. (110), $V_2 = \dfrac{P_1 V_1}{P_2} = \dfrac{14.7 \times 3}{(100 + 14.7)} = 0.385$ *cu. ft.*

3. By For. (115), $P_T = P_{32}[1 + 0.002{,}033(T - 32)] = 60[1 + 0.002{,}033(100 - 32) = 60(1 + 0.138{,}244) = 68.3$ *lb. per sq. in. abs.*

4. By For. (117), $V_T = V_{32}[1 + 0.002{,}033(T - 32)] = 12.39[1 + 0.002{,}033(70 - 32) = 12.39(1 + 0.077{,}254) = 13.35$ *cu. ft.*

5. By For. (121), $P_2 = \dfrac{P_1 \mathrm{T}_2}{\mathrm{T}_1} = \dfrac{14.7 \times (460 + 300)}{(460 + 32)} = 22.7$ *lb. per sq. in. abs.*

6. By For. (122), $\mathrm{T}_2 = \dfrac{\mathrm{T}_1 P_2}{P_1} = \dfrac{(70 + 460) \times (100 + 14.7)}{(60 + 14.7)} = 939.6°$ *F. abs.*, or $(936.6 - 460) = 476.6°$ *F.*

7. By For. (131), $V_2 = \dfrac{V_1 \mathrm{T}_2}{\mathrm{T}_1} = \dfrac{3 \times (1{,}800 + 460)}{(40 + 460)} = 13.56$ *cu. ft.*

8. By For. (132), $\mathrm{T}_2 = \dfrac{\mathrm{T}_1 V_2}{V_1} = \dfrac{(460 + 32) \times 15}{12.39} = 595.6°$ *F. abs.*, or $(595.6 - 460) = 135.6°$ *F.*

9. By Table 244, $V_2' = \dfrac{V_1 P_1}{P_2} = \dfrac{10 \times 1}{2.5} = 4$ cu. ft. Then, $V_2 = \dfrac{V_2' \mathrm{T}_2}{\mathrm{T}_1} = \dfrac{4 \times (80 + 460)}{(50 + 460)} = 4.235$ *cu. ft.*

10. By Table 244, $P_2' = \dfrac{V_1 P_1}{V_2} = \dfrac{10 \times 1}{8} = 1.25$ atmospheres. Then, $P_2 = \dfrac{P_2' \mathrm{T}_2}{\mathrm{T}_1} = \dfrac{1.25 \times (100 + 460)}{(50 + 460)} = 1.373$ *atmospheres.*

11. By Table 244, $\mathrm{T}_2' = \dfrac{\mathrm{T}_1 P_2}{P_1} = \dfrac{(50 + 460) \times 30}{14.7} = 1040.8°$ *F. abs.* Then, $\mathrm{T}_2 = \dfrac{\mathrm{T}_2' V_2}{V_1} = \dfrac{1{,}040.8 \times 5}{10} = 520.4°$ *F. abs.* or $(520.4 - 460) = 60.4°$ *F.*

12. By For. (135), $V_2 = \frac{P_1V_1T_2}{P_2T_1} = \frac{1 \times 10 \times (80 + 460)}{2.5 \times (50 + 460)} = 4.235$ *cu. ft.*

13. By For. (134), $P_2 = \frac{P_1V_1T_2}{V_2T_1} = \frac{14.7 \times 7 \times (200 + 460)}{6 \times (60 + 460)} = 21.67$ *lb. per sq. in abs.*

14. By For. (136), $T_2 = \frac{P_2V_2T_1}{P_1V_1} = \frac{30 \times 5 \times (60 + 460)}{14.7 \times 7} = 758°$ *F. abs.* or $(758 - 460) = 298°$ *F.*

15. From Table 251, for acetylene, $k_G = 59.34$. Hence, by For. (148), *the temperature* $= T = \frac{PV}{Wk_G} = \frac{(200 + 14.7) \times 144 \times 15}{9 \times 59.34} = 868°$ *F. abs.* or, $(868 - 460) = 408°$ *F.*

16. From Table 251, for air, $k_G = 53.34$. Hence, by For. (147), *the volume* $= V = \frac{Wk_GT}{P} = \frac{50 \times 53.34 \times (210 + 460)}{144 \times (250 + 14.7)} = 46.9$ *cu. ft.*

17. By For. (150), $k_G = \frac{PV}{WT} = \frac{144 \times (175 + 14.7) \times 5}{9 \times (290 + 460)} = 20.23.$

18. By For. (149), the *weight originally in the tank* $= W_1 = \frac{P_1V_1}{k_GT_1} = \frac{(144 \times 14.7) \times 10}{53.34 \times (460 + 70)} = 0.75$ *lb.* Also, the *final weight* $= W_2 = \frac{P_2V_2}{k_GT_2} = \frac{144 \times (200 + 14.7) \times 10}{53.34(460 + 75)} = 10.84$ *lb.* Therefore, the *weight forced in* $= W_2 - W_1 = 10.84 - 0.75 = 10.09$ *lb.*

19. By For. (156), $D = \frac{W}{V} = \frac{30.6}{3} = 10.2$ *lb. per cu. ft.*

20. By For. (158), $W = VD = 88 \times 0.08 = 7.04$ *lb.*

21. By For. (165), $D_F = \frac{P_F}{k_GT_F} = \frac{144 \times (100 + 14.7)}{54.99 \times (460 + 80)}$ $= 0.556$ *lb. per cu. ft.*

22. By For. (159*A*), $D_2 = \frac{D_1P_2}{P_1} = \frac{0.556 \times 14.7}{(100 + 14.7)} = 0.071,3$ *lb. per cu. ft.*

23. By For. (164), $D_2 = \frac{D_1T_1P_2}{T_2P_1} =$

$$\frac{0.556 \times (460 + 80) \times (1{,}800 + 14.7)}{(460 + 200) \times (100 + 14.7)} = 7.2 \text{ lb. per cu. ft.}$$

24. The average pressures are as follows: along *ab*, 60 lb. per sq. ft.; along *bc*, 65; along *cd*, 60; along *de*, 55; and along *ef*, 50. Hence, since *work* = (*average pressure*) × (*change in volume*), the *work* = $(60 \times 2) + (65 \times 1) + (60 \times 3) + (55 \times 1) + (50 \times 1) = 470$ *ft.-lb.*

25. By For. (149), the *weight* $= W = \frac{PV}{k_GT} = \frac{(150 + 14.7) \times 144 \times 40}{53.34 \times (460 + 70)} = 33.6$ *lb.* Also, by For. (122), the *initial temperature* $= T_1 = \frac{P_1T_2}{P_2} = \frac{(14.7 + 200) \times (460 + 70)}{(14.7 + 150)} = 691°$ *F. abs.*, or $(691 - 460) = 231°$ *F.* Hence, by For. (175), the *heat added* $= WC_V(T_2 - T_1) = 33.6 \times 0.171 \times$

$(70 - 231) = -925$ *B.t.u.*, or 925 *B.t.u. have been extracted.* Also, by For. (177), the *vibration work* $= W_V = 778WC_V(T_2 - T_1) = 778 \times 33.6 \times 0.171 \times (70 - 231) = -719{,}500$ *ft.-lb.*

26. From Table 251, for air, $C_P = 0.241$ and $C_V = 0.171$. Hence, by For. (178), *heat added* $= Q = WC_P(T_2 - T_1) = 6 \times 0.241 \times (150 - 60) = 130.1$ *B.t.u.* By For. (180), *external work* $= W_E = 778W(C_P - C_V)(T_2 - T_1) = 778 \times 6 \times (0.241 - 0.171) \times (150 - 60) = 29{,}400$ *ft.-lb.* By For. (182), the *vibration work* $= 778WC_V(T_2 - T_1) = 778 \times 6 \times 0.171 \times (150 - 60) = 71{,}850$ *ft.-lb.*

27. By For. (132), the *final temperature* $= T_2 = \dfrac{T_1V_2}{V_1} = \dfrac{(460 + 130) \times 90}{100} = 531^\circ$ *F. abs.* or $(531 - 460) = 71^\circ$ *F.* By For. (149), the *weight* $= W = \dfrac{PV}{k_GT} = \dfrac{(100 + 14.7) \times 144 \times 100}{53.34 \times (460 + 130)} = 52.55$ *lb.* Hence, by For. (178) the *heat added* $= Q = WC_P(T_2 - T_1) = 52.55 \times 0.241 \times (130 - 71) = -747$ *B.t.u.* Hence, *heat abstracted* = 747 *B.t.u.* By For. (179), *external work* $= W_E = P(V_2 - V_1) = 144 \times (100 + 14.7)(90 - 100) = -165{,}200$ *ft.-lb.* By For. (182), *vibration work* $= W_V = 778WC_V(T_2 - T_1) = 778 \times 52.55 \times 0.171 \times (71 - 130) = -412{,}500$ *ft.-lb.*

28. By For. (192), the *work done* $= W_E = P_1V_1 \log_e \dfrac{P_1}{P_2} = 144 \times 14.7 \times 3 \times \log_e \dfrac{14.7}{100 + 14.7} = 6{,}350 \times \log_e 0.128{,}1$. Now, $\log 0.128{,}1 = 9.107{,}7 - 10 = -0.892{,}3$. Therefore, $\log_e = 2.303 \times (-0.892{,}3) = -2.054$. Hence, $W_E = 6{,}350 \times (-2.054) = -13.040$ *ft.-lb.* By For. (194), the *heat added* $= Q = \dfrac{W_E}{778} = \dfrac{-13{,}040}{778} = -16.77$ *B.t.u.* or, the *heat abstracted* = 16.77 *B.t.u.* The heat comes from the external work done *on the gas.*

29. For. (193) may be written: $W_E = Wk_GT \log_e \dfrac{P_1}{P_2}$. Hence, the *external work* $= W_E = 1 \times 53.34 \times (460 + 100) \log_e \dfrac{175 + 14.7}{15 + 14.7} = 29{,}880 \times \log_e 6.39$. Now, $\log 6.39 = 0.805{,}5$. Hence, $\log_e 6.39 = 2.303 \times 0.805{,}5 = 1.854$. Therefore, $W_E = 29{,}880 \times 1.854 = 55{,}400$ *ft.-lb.*

30. By For. (202), *external work* $= W_E = 778WC_V(T_1 - T_2) = 778 \times 20 \times 0.171 \times (80 - 150) = -186{,}200$ *ft.-lb.* Hence, 186,200 ft.-lb. of external work was done *on* the gas.

31. By For. (147), the *initial volume* $= V_1 = \dfrac{Wk_GT_1}{P_1} = \dfrac{1 \times 53.34 \times (200 + 460)}{300 \times 144} = 0.815$ *cu. ft.* By For. (235) the *final volume* $= V_2 = V_1 \left(\dfrac{P_1}{P_2}\right)^{\frac{1}{k}} = 0.815 \times \left(\dfrac{300}{15}\right)^{\frac{1}{1.4}} = 0.815 \times (20)^{0.714}$. Now, $\log 20 = 1.301{,}0$. Hence, $\log (20)^{0.714} = 0.714 \times 1.301{,}0 = 0.929$. Also,

$0.929 = \log 8.49$. Hence $(20)^{0.714} = 8.49$. Therefore, $V_2 = 0.815 \times 8.49 = 6.92$ *cu. ft.* By For. (236), the *final temperature* $= T_2 = T_1 \left(\frac{P_2}{P_1}\right)^{\frac{k-1}{k}} = (460 + 200) \times \left(\frac{15}{300}\right)^{\frac{1.4-1}{1.4}} = 660 \times (0.05)^{0.286}$. Now, $\log 0.05 = 8.699 - 10 = -1.301$. Hence, $\log (0.05)^{0.286} = 0.286 \times (-1.301) = -0.371{,}8$. Also, $-0.371{,}8 = 9.628{,}2 - 10 = \log 0.425$. Hence, $(0.05)^{0.286} = 0.425$. Therefore, $T_2 = 660 \times 0.425 = 280°$ *F. abs.* or $(280 - 460) = -180°$ *F.*

32. By For. (201), the *external work* $= W_E = \frac{P_1V_1 - P_2V_2}{k - 1} = \frac{(144 \times 300 \times 0.815) - (144 \times 15 \times 6.92)}{1.40 - 1} = 50{,}600$ *ft.-lb.* By For. (204), the *vibration work* $= W_V = 778WC_V(T_2 - T_1) = 778 \times 1 \times 0.171 \times (-180 - 200) = -50{,}600$ *ft.-lb.*

33. By For. (235), the *final volume* $= V_2 = V_1\left(\frac{P_1}{P_2}\right)^{\frac{1}{k}} = 10 \times \left(\frac{14}{60}\right)^{\frac{1}{1.4}} = 10 \times (0.233{,}3)^{0.714}$. Now, $\log 0.233{,}3 = 9.368 - 10 = -0.632$. Hence, $\log (0.233{,}3)^{0.714} = 0.714 \times (-0.632) = -0.456{,}4 = 9.543{,}6 - 10$. But, $9.543{,}6 - 10 = \log 0.349{,}7$. Hence, $(0.233{,}3)^{0.714} = 0.3497$. Therefore, $V_2 = 10 \times 0.349{,}7 = 3.497$ *cu. ft.* By For. (236), $T_2 = T_1\left(\frac{P_2}{P_1}\right)^{\frac{k-1}{k}} = (460 + 100)\left(\frac{60}{14}\right)^{\frac{1.4-1}{1.4}} = 560 \times (4.287)^{0.286}$. Now, $\log 4.287 = 0.632$. Hence, $\log (4.287)^{0.286} = 0.286 \times 0.632 = 0.180{,}7$. But, $0.180{,}7 = \log 1.515{,}5$. Hence, $(4.287)^{0.286} = 1.515{,}5$. Therefore. $T_2 = 560 \times 1.515{,}5 = 849°$ *F. abs.*, or $(849 - 460) = 389°$ *F.*

34. By For. (222), the *specific heat* $= C = \frac{n - k}{n - 1} C_V = \frac{1.2 - 1.4}{1.2 - 1} \times 0.171 = -0.171$. By For. (219), the *external work* $= W_E = 778W(C - C_V)(T_2 - T_1) = 778 \times 20 \times (-0.171 - 0.171)(150 - 80) = -372{,}400$ *ft.-lb.* By For. (217), the *heat added* $= Q = WC(T_2 - T_1) = 20 \times (-0.171) \times (150 - 80) = -239.4$ *B.t.u.*, or 239.4 B.t.u. had to be *abstracted.*

35. By transposing For. (223), the *vibration work* $= W_V = 778Q - W_E = 778 \times 8 - 40{,}000 = -33{,}776$ *ft.-lb.*

36. By For. (222), the *specific heat* $= C = \frac{n - k}{n - 1} C_V = \frac{1.3 - 1.4}{1.3 - 1} \times 0.171 = -0.057$. Hence, by For. (217), the *heat added* $= Q = WC(T_2 - T_1) = 1 \times (-0.057) \times (200 - 80) = -6.84$ *B.t.u.* Or, the *heat abstracted* $= 6.84$ *B.t.u.*

37. By For. (147), the *initial volume* $= V_1 = \frac{Wk_GT_1}{P_1} = \frac{1 \times 54.99 \times (460 + 120)}{144 \times (100 + 14.7)} = 1.93$ *cu. ft.* By For. (235), the *final volume* $= V_2 = V_1\left(\frac{P_1}{P_2}\right)^{\frac{1}{n}} = 1.93\left(\frac{100 + 14.7}{14.7}\right)^{\frac{1}{1.35}} = 1.93 \times (7.805)^{0.741}$.

Now, log 7.805 = 0.892,2. Hence, log $(7.805)^{0.741} = 0.741 \times 0.892{,}2 = 0.661 = \log 4.58$. Therefore, $V_2 = 1.93 \times 4.58 = 8.84$ *cu. ft.* By For. (236), the *final temperature* $= \mathrm{T}_2 = \mathrm{T}_1\left(\frac{P_2}{P_1}\right)^{\frac{n-1}{n}} = (460 + 120)\left(\frac{14.7}{114.7}\right)^{\frac{1.35-1}{1.35}}$ $= 580 \times (0.128{,}1)^{0.259{,}2}$. Now, $\log 0.128{,}1 = 9.107{,}8 - 10 = -0.892{,}2$. Hence, $\log (0.128{,}1)^{0.259{,}2} = 0.259{,}2 \times (-0.892{,}2) = -0.231{,}3 = 9.768{,}7 - 10 = \log 0.587$. Therefore, $\mathrm{T}_2 = 580 \times 0.587 = 323°$ *F. abs*, or $(323 - 460) = -137°$ *F.*

38. By For. (218), the *external work* $= W_E = \frac{P_1V_1 - P_2V_2}{n-1} = \frac{(144 \times 114.7 \times 1.93) - (144 \times 14.7 \times 8.84)}{1.35 - 1} = 37{,}660$ *ft.-lb.* By For. (220), the *vibration work* $= W_V = 778\mathrm{W}C_V(T_2 - T_1) = 778 \times 1 \times 0.176 \times (-137 - 120) = -35{,}180$ *ft.-lb.* By For. (223) transposed, the *heat added* $= \mathrm{Q} = (W_E + W_V)/778 = (37{,}660 - 35{,}180) \div 778 = 3.19$ *B.t.u.*

39. From Table 251, for oxygen, $\mathrm{k} = 1.4$. Hence, by For. (238), the *final pressure* $= P_2 = P_1\left(\frac{\mathrm{T}_2}{\mathrm{T}_1}\right)^{\frac{\mathrm{k}}{\mathrm{k}-1}} = 1{,}800\left(\frac{460 - 280}{460 + 90}\right)^{\frac{1.4}{1.4-1}} = 1{,}800 \times (0.327{,}3)^{3.5}$. Now, $\log 0.327{,}3 = 9.515{,}0 - 10 = -0.485{,}0$. Hence, $\log (0.327{,}3)^{3.5} = 3.5 \times (-0.485{,}0) = -1.697 = 8.303 - 10 = \log 0.020{,}1$. Therefore, $P_2 = 1{,}800 \times 0.020{,}1 = 36.18$ *lb. per sq. in. abs.* By For. (239), the *final volume* $= V_2 = V_1\left(\frac{\mathrm{T}_1}{\mathrm{T}_2}\right)^{\frac{1}{\mathrm{k}-1}} = 2 \times \left(\frac{460 + 90}{460 - 280}\right)^{\frac{1}{1.4-1}}$ $= 2 \times (3.056)^{2.5}$. Now, $\log 3.056 = 0.485{,}2$. Hence, $\log (3.056)^{2.5} = 2.5 \times 0.485{,}2 = 1.212{,}5 = \log 16.31$. Therefore, $V_2 = 2 \times 16.31 = 32.62$ *cu. ft.*

SOLUTIONS TO PROBLEMS ON DIVISION 9

MELTING AND FREEZING OF SUBSTANCES

1. By Table 90 the specific heat of ice = 0.504 B.t.u. per lb. By Table 291 the latent heat of melting of ice = 143.3 B.t.u. per lb. Hence, the required heat $= \{[0.504 \times (32 - 22)] + 143.3\} \times 300 = 44{,}502$ *B.t.u.*

2. By Table 90 the specific heat of water = 1.0 B.t.u. per lb. By Table 291 the latent heat of melting of ice = 143.3 B.t.u. per lb. Hence, the heat passing to the brine $= [1.0 \times (65 - 32) + 143.3] \times 258.3 = 45{,}538$ *B.t.u.*

3. By note subjoined to Sec. 288 the approximate freezing temperature $= 32 - \left[0.0135\left(\frac{110}{14.7}\right)\right] = 31.899°$ F.

4. By Table 285 the melting temperature of tin = 449° F. By Table 90 the specific heat of solid tin = 0.055 B.t.u. per lb. By Table 291 the latent heat of fusion of tin = 25.2 B.t.u. per lb. By Table 90 the specific heat of molten tin = 0.058 B.t.u. per lb. Hence the quantity of heat absorbed = 2,000 × {[0.055 × (449 − 80)] + 25.2 + [0.058 × (660 − 449)]} = 115,466 *B.t.u.*

SOLUTIONS TO PROBLEMS ON DIVISION 10

VAPORIZATION

1. By Table 90, the specific heat of water = 1.0 B.t.u. per lb. By Table 323 the latent heat of vaporization of water under atmospheric pressure = 970.4 B.t.u. per lb. By Table 318 the boiling temperature of water under atmospheric pressure = 212° F. Therefore the requisite quantity of heat = 1.0 × (212 − 32) + 970.4 = 1150.4 *B.t.u.*

2. By Table 291, the latent heat of melting of ice = 143.3 B.t.u. per lb By Table 90, the specific heat of water = 1.0 B.t.u. per lb. By Table 323 the latent heat of vaporization of water under atmospheric pressure = 970.4 B.t.u. per lb. By Table 318 the boiling temperature of water under atmospheric pressure = 212° F. Therefore, the requisite quantity of heat = 143.3 + [1.0 × (212 − 32)] + 970.4 = 1293.7 *B.t.u.*

3. By Table 332 the weight of water vapor per cubic foot of air at 70° F., for a relative humidity of 50 per cent., = 3.99 grains. Therefore, the weight per cubic foot for a relative humidity of 55 per cent. = $\frac{3.99}{50} \times 55 = 4.389$ *grains.*

4. The *temperature difference* = 70 − 53 = 17° F. By Table 335, the relative humidity = 30 per cent. From Table 332, the *weight of vapor* = 2.394 *grains per cubic foot.*

5. Following downward to the right from the 75° wet-bulb mark to the vertical line through the 90° dry-bulb mark, the relative humidity is found, at the intersection, to be 50 *per cent.* The weight of moisture in 1 cu. ft. of saturated air at 90° F. is shown by curve *F* to be 15 *grains per cu. ft.* Hence, for 50-per cent. relative humidity, *the weight of water vapor* = 0.50 × 15 = 7.5 *grains per cu. ft.*

6. Following upward from the 90° dry-bulb mark to the 80-per cent. relative-humidity line, the wet-bulb temperature is found to be 84.5° *F.* The *moisture added* = (0.80 − 0.50) × 15 = 4.5 *grains per cu. ft.*

7. The intersection of the 75° F. wet-bulb line and the 80-per cent. relative-humidity line gives a dry-bulb temperature of 80° *F.*

8. From Fig. 328, the states are: (*a*) Gaseous. (*b*) Gaseous. (*c*) Liquid. (*d*) Gaseous.

9. From Fig. 329, the states are: (*a*) Gaseous. (*b*) Gaseous. (*c*) Liquid. (*d*) Gaseous.

SOLUTIONS TO PROBLEMS ON DIVISION 11

STEAM AND OTHER VAPORS

1. As given in Steam Table 394 for 20 lb. per sq. in. abs., **h** = 196.1 *B.t.u. per lb.* and **L** = 960.0 *B.t.u. per lb.* Then by For. (242), *the heat* *content of* 1 *lb. of wet steam* = $\mathbf{H}_W = \mathbf{h} + \mathbf{xL} = 196.1 + (0.928 \times 960) = 196.1 + 890.9 = 1{,}087$ *B.t.u. per lb.* Heat in condensate at 60° F. is **h** at 60° F. which by interpolating the values given in Steam Table 394 is found to be 28.08 B.t.u. *Heat given up by* 1 *lb. of steam* = $\mathbf{H}_W - \mathbf{h}$ at 60° F. The *total heat given off during condensation* = 1,500 ($\mathbf{H}_W - \mathbf{h}$ at 60° F.) = $1{,}500\ (1{,}087.0 - 28.1) = 1{,}500 \times 1{,}058.9 = 1{,}588{,}350$ *B.t.u.*

2. As given in Steam Table 394, temperature corresponding to 185 lb. per sq. in. gage is 381.9° F. Thus, the steam at 432° F. has 432°–381.9° or 50.1° F. superheat. Heat content of steam at 185 lb. per sq. in. gage, and 50.1° superheat is found to be, by interpolating the values given in Table 395:

$$1{,}223.9 + \frac{(1{,}235.5 - 1{,}223.9)10.1}{20} = 1{,}229.8 \text{ } \textit{B.t.u. per lb.}$$

Heat content of 1 *lb. of water at* 49° *F.* = 49 − 32 = 17 *B.t.u.* Then, *heat added to* 1 *lb. of water* = 1,229.8 − 17.0 = 1,212.8 B.t.u. *Total heat added to* 1,720 *lb. of water* = $1{,}720 \times 1{,}212.8 = 2{,}086{,}016$ *B.t.u.*

3. As given in Steam Table 394 for 140 lb. per sq. in. abs., $\mathbf{h} = 324.6$ *B.t.u. per lb.* and $\mathbf{L} = 867.6$ *B.t.u. per lb.* and for 2 lb. per sq. in. abs., $\mathbf{h} = 94.0$ *B.t.u. per lb.* and $\mathbf{L} = 1{,}021.0$ *B.t.u. per lb.* Then, by For. (242), *heat content of* 1 *lb. of wet steam entering turbine* $\mathbf{h} + \mathbf{xL} = 324.6 + (0.98 \times 867.6) = 324.6 + 850.2 = 1{,}174.8$ *B.t.u. per lb. Heat content of* 1 *lb. exhaust steam* = $\mathbf{h} + \mathbf{xL} = 94.0 + (0.81 \times 1{,}021.0) = 94.0 + 827.0 = 921.0$ *B.t.u. per lb. Heat absorbed from* 1 *lb. of steam* = $1{,}174.8 - 921.0 = 253.8$ *B.t.u.*

4. By Table 394, the specific volumes of dry saturated steam at 140 and 2 lb. per sq. in. abs. are 3.219 and 173.5 cu. ft. per lb. respectively. Hence, by For. (245), the *specific volume of the entering steam* = $V_W = \mathbf{x}V_D = 0.98 \times 3.219 = 3.154$ *cu. ft. per lb.* Also, *the specific volume of the exhaust steam* = $0.81 \times 173.5 = 140.5$ *cu. ft. per lb.*

5. From Prob. 3, the total heat of the entering steam = $\mathbf{H}_1 = 1{,}174.8$ *B.t.u. per lb.* and that of the exhaust steam = $\mathbf{H}_2 = 921.0$ *B.t.u. per lb.* The specific volumes were found in Prob. 4. Hence, by For. (248), the *internal energy of the entering steam* = $\mathbf{I}_1 = \mathbf{H}_1 - 0.185{,}2P_1V_1 = 1{,}174.8 - (0.185{,}2 \times 140 \times 3.219) = 1{,}091.3$ *B.t.u. per lb.* And, the *internal energy of the exhaust steam* = $\mathbf{I}_2 = \mathbf{H}_2 - 0.185{,}2\,P_2V_2 = 921.0 - (0.185{,}2 \times 2 \times 140.5) = 869.0$ *B.t.u. per lb.*

6. As given in Steam Table 394, for 140 lb. per sq. in. abs., $\mathbf{n}_L = 0.507{,}2$ and $\mathbf{n}_V = 1.067{,}5$; for 2 lb. per sq. in. abs., $\mathbf{n}_L = 0.174{,}9$ and $\mathbf{n}_V = 1.743{,}1$. By For. (260) *entropy for wet vapor* $= \mathbf{n}_W = \mathbf{n}_L + \mathbf{x}\mathbf{n}_X$ *Entropy of steam at beginning of expansion* = $\mathbf{n}_L + \mathbf{x}\mathbf{n}_V = 0.507.2 + (0.98 \times 1.067{,}5) = 0.507{,}2 + 1.046{,}1 = 1.553{,}3$. *Entropy of steam at exhaust* = $\mathbf{n}_L + \mathbf{x}\mathbf{n}_V = 0.174{,}9 + (0.81 \times 1.743{,}1) = 0.174{,}9 + 1.411{,}9 = 1.586{,}8$. *The increase in entropy* = $1.586{,}8 - 1.553{,}3 = 0.033{,}5$. *The heat in the exhaust in excess of that which would be contained had the steam expanded isentropically* = (*difference in entropy*) × (*absolute temperature of exhaust steam*) = $0.033{,}5\ (460 + 126) = 0.033{,}5 \times 586 = 19.63$ *B.t.u. per lb.*

7. Locate on heat-entropy chart (Fig. 343) the point at the intersection of the 160 lb. per sq. in. abs. pressure line and the 40° *F.* superheat line. Now follow down a constant entropy line, which is a vertical line, until the constant pressure line of 0.5 lb. per sq. in. abs. is reached. The point thus located lies between the constant quality lines 0.77 and 0.78 at about ⅕ the distance between them from the 0.77 line. The quality is then 0.772 or 77.2 per cent.

To find the quality after expansion by means of the tables, the entropy values are used since the entropy remains constant during the expansion. As given in Table 395, the entropy of steam at 160 lb. per sq. in. abs. and 40° F. superheat is 1.592,8. Now the entropy at the end of expansion must be the same as that at the beginning, or 1.592,8; since it is a constant entropy expansion. In working a problem of this type it is generally well to draw a temperature-entropy diagram, it need not be to scale but ust to picture what occurs, as in Fig. 631.

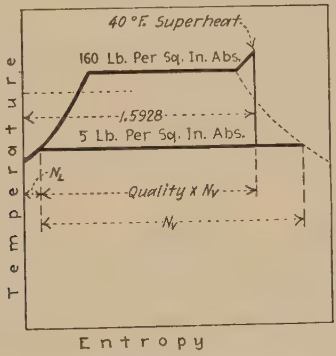


FIG. 631.—Temperature-entropy diagram for problem 7. (Note not to scale.)

By For. (265):

$$x = \frac{(\mathbf{n}_W - \mathbf{n}_L)}{\mathbf{n}_V}$$

As given in Steam Table 394 for 0.5 lb. per sq. in. abs., $\mathbf{n}_L = 0.092,3$ and $\mathbf{n}_V = 1.942,0$.

Then, the quality after expansion =

$$x = \frac{(\mathbf{n}_W - \mathbf{n}_L)}{\mathbf{n}_V} = \frac{(1.592,8 - \mathbf{n}_L)}{\mathbf{n}_V} = \frac{(1.592,8 - 0.092,3)}{1.942,0} = 0.772,6$$

or 77.26 *per cent.*

This value checks closely with that of 77.2 per cent. found by using the chart.

8. From the heat-entropy chart (Fig. 343), the total heat of the supply steam = $\mathbf{H}_1$ = 1,257 *B.t.u. per lb.*, and the total heat of the steam after expansion = 958 *B.t.u. per lb.* Also, the quality of the steam after expansion = 83.7 per cent. Now, from Table 395, the specific volume of the supply steam = 2.68 *cu. ft. per lb.* and from Table 394 the specific volume of dry saturated steam at 3 lb. per sq. in. abs. = 118.5 *cu. ft. per lb.* Hence, by For. (245) the specific volume of the steam after expansion = $V_W = xV_D = 0.837 \times 118.5 = 98.2$ *cu. ft. per lb.* Therefore, by For. (269), the *external work* = $W_E = 778(H_1 - H_2) + 144(P_2V_2 - P_1V_1) = 778 \times (1{,}257 - 958) + [144 \times (3 \times 98.2 - 200 \times 2.68)] =$ 197,860 *ft.-lb. per pound of steam.*

9. Values for the solution of this problem are taken from ammonia table 400. By For. (242), the *total heat before expansion* = $H_{W1} = h + xL = -44.2 + (0.10 \times 535.7) = 9.4$ *B.t.u. per lb.* Also, the *total heat after expansion* = $H_{W2} = -44.2 + (0.95 \times 535.7) = 464.7$ *B.t.u. per lb.* Therefore, by For. (275), the *heat absorbed* = $Q = H_2 - H_1 = 464.7 - 9.4 = 455.3$ *B.t.u. per pound of ammonia.* Now, by For. (245), the *specific volume before expansion* = $V_{W1} = xV_D = 0.10 \times 11.63 = 1.163$ *cu. ft. per lb.* Also, the *specific volume after expansion* = $V_{W2} = 0.95 \times 11.63 = 11.05$ *cu. ft. per lb.* Hence, by For. (277), the *external work* = $W_E = 144P(V_2 - V_1) = 144 \times 23.3 \times (11.05 - 1.163) =$ 33,173 *ft.-lb. per pound of ammonia.*

10. As given in Steam Table 394, for dry saturated steam at 346° F., $h = 317.1$ *B.t.u. per lb.* and $L = 873.4$ *B.t.u. per lb.* Hence, by For. (278), the *quality* =

$$x = \frac{1{,}050 + 0.46\,T_2 - h}{L} = \frac{1{,}050 + (0.46 \times 256) - 317.1}{873.4} = 0.974;$$

or, *quality* = 97.4 *per cent.*

SOLUTIONS TO PROBLEMS ON DIVISION 12

GAS AND VAPOR CYCLES

1. By For. (283): *Thermal efficiency* = $\dfrac{\textit{Heat converted into work}}{\textit{Heat supplied from hot body}} = \dfrac{68{,}000}{200{,}000} = 0.34$, or 34 *per cent.*

2. By For. (284): *Coefficient of performance* =

$$\frac{\textit{Heat abstracted from cold body}}{\textit{Heat equivalent of energy supplied}} = \frac{800{,}000}{194{,}500{,}000 \div 778} = 3.20.$$

3. By For (292), *the efficiency* = $E = \dfrac{T_H - T_C}{T_H} = \dfrac{2{,}800 - 60}{2{,}800 + 460} =$ 0.84, or 84 *per cent.*

4. By For. (298), *the coefficient of performance* = $\dfrac{T_C}{T_H - T_C} =$

$$\frac{0 + 460}{90 - 0} = 5.11.$$

5. According to the claim, the *efficiency* = $\dfrac{2{,}545}{\frac{1}{3} \times 18{,}000} = 0.424.$ A Carnot engine would by For. (292) have an efficiency = $E = \dfrac{T_H - T_C}{T_H} = \dfrac{2{,}700 - 850}{2{,}700 + 460} = 0.586.$ Therefore, the claim does not violate the principle stated in Sec. 416.

6. From the Mollier diagram, Fig. 343, the *total heat* of steam at 150 lb. per sq. in. abs. and 250° F. superheat = $\mathbf{H}_1$ = 1,324 *B.t.u. per lb.* Also, after isentropic expansion down to 1 lb. per sq. in. abs., the *total heat* = $\mathbf{H}_2$ = 954 *B.t.u. per lb.* From Steam Table 394, the *heat of the liquid* at the temperature corresponding to 1 lb. per sq. in. abs. = $\mathbf{h}_2$ = 69.8 *B.t.u. per lb.* Hence, by For. (299), the *efficiency* = $\mathbf{E}$ = $\frac{\mathbf{H}_1 - \mathbf{H}_2}{\mathbf{H}_1 - \mathbf{h}_2} = \frac{1{,}324 - 954}{1{,}324 - 69.8}$ = 0.295, or 29.5 *per cent.*

7. Since, in the Rankine cycle, the work done per pound of steam is—For. (302)—$\mathbf{H}_1 - \mathbf{H}_2$, in this problem the *work* = 1,324 − 954 = 370 *B.t.u. per lb. of steam.* Now, since 1 hp.-hr. = 2,545 *B.t.u.*, the necessary *weight* = 2,545 ÷ 370 = 6.88 *lb. per hp.-hr.*

8. Since 1 gal. (231 cu. in.) of water weighs 8.33 lb., 5 lb. of water will occupy 231 × 5 ÷ 8.33 = 138.8 *cu. in.* This is volume V_C, Fig. 377. Now, the *displacement volume* = 0.785 × 6 × 6 × 15 = 424 *cu. in.* Hence, V_B (Fig. 377) = 138.8 + 424 = 562.8 *cu. in.* Therefore, by For. (307), the *efficiency* = $\mathbf{E} = 1 - \left(\frac{V_C}{V_B}\right)^{k-1} = 1 - \left(\frac{138.8}{562.8}\right)^{1.4-1}$ = 0.429 or 42.9 *per cent.*

9. The *clearance volume* = 0.05 × 6 = 0.3 *cu. ft.* Hence, point *F*, Fig. 381, represents a volume of 0.3 cu. ft. and a pressure of 100 lb. per sq. in. gage or 114.7 lb. per sq. in. abs. The pressure at point *A*, Fig. 381, is 5 lb. per sq. in. gage or 19.7 lb. per sq. in. abs. To find the volume at *A*, use For. (235) thus: $V_A = V_F\left(\frac{P_F}{P_A}\right)^{\frac{1}{n}} = 0.3\left(\frac{114.7}{19.7}\right)^{\frac{1}{1.3}} = 1.16$ *cu. ft.* Hence, the *low pressure capacity* = 6 + 0.3 − 1.16 = 5.14 *cu. ft.* Now, by For. (310), the *volumetric efficiency* = (*Low-pressure capacity*) ÷ (*Displacement volume*) = 5.14 ÷ 6 = 0.857 or 85.7 *per cent.*

10. The *clearance volume* (V_F, Fig. 381) = 0.04 × 8 = 0.32 *cu. ft.* By For. (235), $V_A = V_F\left(\frac{P_F}{P_A}\right)^{\frac{1}{k}} = 0.32\left(\frac{70 + 14.7}{14.7}\right)^{\frac{1}{1.4}} = 1.117$ *cu. ft.* *Low-pressure capacity* = $V_B - V_A$ = (8 + 0.32) − 1.117 = 7.203 *cu. ft.*

11. By For. (311): $P = \sqrt{P_1P_2} = \sqrt{(14.7) \times (110 + 14.7)} = 42.8$ *lb. per sq. in. abs.*, or (42.8 − 14.7) = 28.1 *lb. per sq. in. gage.*

12. Letting Figs. 385 and 386 represent the cycle (but understanding that compression is adiabatic instead of polytropic as shown in these figures), the given data is: $T_D = 34°$ F $P_E = P_D = 40$ lb. per sq. in. gage = 54.7 lb. per sq. in. abs. $P_C = P_B = 130$ lb. per sq. in. gage = 144.7 lb. per sq. in. abs. $T_B = 70°$ F. By For. (236), $\mathrm{T}_E = \mathrm{T}_B\left(\frac{P_E}{P_B}\right)^{\frac{k-1}{k}} = (70 + 460)\left(\frac{54.7}{144.7}\right)^{\frac{1.4-1}{1.4}}$ = 401° *F. abs.*, or $T_E = -59°$ *F.* Also, $\mathrm{T}_C = \mathrm{T}_D\left(\frac{P_C}{P_D}\right)^{\frac{k-1}{k}} = (34 + 460)\left(\frac{144.7}{54.7}\right)^{\frac{1.4-1}{1.4}}$ = 652° *F. abs.*, or $T_C = 192°$ *F.* Hence, for 1 lb. of air, the *heat abstracted from the cold* *room* = $C_P(T_D - T_E) = 0.002{,}41 \times [34 - (-59)] = 0.224$ *B.t.u.*, and the *heat rejected to the cooling water* = $C_P(T_C - T_B) = 0.002{,}41 \times (192 - 70) = 0.294$ *B.t.u.* Also, the *work done* = (*heat rejected by cooling water*) − (*heat abstracted from cold room*) = 0.294 − 0.224 = 0.07 *B.t.u.* Hence, by For. (284) the *coefficient of performance* =

$$\frac{\textit{Heat abstracted from cold body}}{\textit{Heat supplied as work}} = \frac{0.224}{0.07} = 3.2.$$

13. *Weight circulated* = 2,000 ÷ 0.224 = 8,930 *lb. per hr. Power* = 8,930 × 0.07 = 625 *B.t.u. per hr.*, or 625 ÷ 2.545 = 0.246 *hp.*

14. By Table 400, the pressure corresponding to 80° F. is 153.9 *lb. per sq. in. abs.*, and the pressure corresponding to 20° F. is 47.75 *lb. per sq. in. abs.*

15. Referring to Fig. 387, the *heat abstracted* is represented by the area $B\,BCC'$ which is numerically equal to $\mathbf{H}_C - \mathbf{H}_B$. Now, from Table 400, $\mathbf{H}_C = 543.7$ *B.t.u. per lb.* Also, $\mathbf{H}_B = \mathbf{h}_A$ (which, from Table 400) = 47.8 *B.t.u. per lb.* Hence, *heat abstracted* = $\mathbf{H}_C - \mathbf{H}_B = 543.7 - 47.8 = 495.9$ *B.t.u. per lb.* Therefore, to abstract 2,000 *B.t.u. per hour,* there must be *circulated:* 2,000 ÷ 459.9 = 4.04 *lb. per hr.*

16. By Sec. 434, the *mechanical efficiency* = $\dfrac{\textit{Shaft output}}{\textit{Indicated work}} = \dfrac{9{,}537}{11{,}220} =$ 0.85 or 85 *per cent.*

17. By Sec. 434, the *mechanical efficiency* = $\dfrac{\textit{Indicated work}}{\textit{Shaft input}} = \dfrac{3{,}300 \times 200}{25 \times 33{,}000} = 0.80$ or 80 *per cent.*

18. By Steam Table 394, the temperature of dry saturated steam at 115.3 lb. per sq. in. gage or 130 lb. per sq. in. abs. is 347.4° F. At 0.3 lb. per sq. in. gage or 15 lb. per sq. in. abs., the temperature is 213° F. Hence, by For. (292), the *ideal Carnot efficiency* = $\mathbf{E} = \dfrac{\mathbf{T}_H - \mathbf{T}_C}{\mathbf{T}_H} = \dfrac{347.4 - 213}{(347.4 + 460)} = 0.166{,}6$ or 16.66 *per cent.* From the Mollier chart (Fig. 343), the *total heat of dry saturated steam at* 130 *lb. per sq. in. abs.* = $\mathbf{H}_1 = 1{,}191$ *B.t.u. per lb.*, and after isentropic expansion to 15 lb. per sq. in. abs. the *total heat* = $\mathbf{H}_2 = 1{,}034$ *B.t.u. per lb.* By Steam Table 394, the *heat of the liquid* at 213° F. = $\mathbf{h}_2 = 181$ *B.t.u. per lb.* Hence, by For. (299), the *ideal Rankine efficiency* = $\mathbf{E} = \dfrac{\mathbf{H}_1 - \mathbf{H}_2}{\mathbf{H}_1 - \mathbf{h}_2} = \dfrac{1{,}191 - 1{,}034}{1{,}191 - 181} = 0.141{,}4$ or 14.14 *per cent.* By For. (317) the *cylinder efficiency* = $\dfrac{\textit{Indicated work}}{\textit{Work of theoretical engine}} = \dfrac{130 \times 2{,}545}{3{,}965(1{,}191 - 1{,}034)} = 0.531{,}5$ or 53.15 *per cent.* By For. (314), the *actual thermal efficiency* = $\dfrac{\textit{Indicated work}}{\textit{Heat input}} = \dfrac{130 \times 2{,}545}{3{,}965 \times (1{,}191 - 181)} = 0.075{,}2$ or 7.52 *per cent.* By For. (318), the *mechanical efficiency* = $\dfrac{\textit{Shaft output}}{\textit{Indicated work}} = \dfrac{120}{130} = 0.924$

or 92.4 *per cent.* By For. (315), the *overall efficiency* = $\frac{\textit{Shaft output}}{\textit{Heat input}}$ = $\frac{120 \times 2{,}545}{3{,}965 \times (1{,}191 - 181)}$ = 0.069,4 or 6.94 *per cent.*

SOLUTIONS TO PROBLEMS ON DIVISION 13

FUELS

1. *Total content by percentage,* eliminating moisture = 25.00 + 57.35 + 5.15 = 87.50 *per cent.* $\frac{25.00}{87.50}$ = 28.55 *per cent.* volatile; $\frac{57.35}{87.50}$ = 65.55 *per cent.* fixed carbon; $\frac{5.15}{87.50}$ = 5.90 *per cent.* ash in the Dry Coal. *Total content by percentage,* eliminating ash = 28.55 + 57.35 = 85.00 *per cent.* $\frac{28.55}{85.90}$ = 33.25 per cent. volatile. $\frac{57.35}{85.90}$ = 66.75 per cent. fixed carbon; in the combustible.

2. $\frac{33.25}{66.75}$ = 0.5. From Fig. 407, it is found that a coal having ratio of volatile to fixed carbon of .5 has a *heating value* of *approximately* 15 400 *B.t.u. per lb. of combustible.*

3. *Ratio of volatile* to *carbon* in the first instance = $^{16}/_{64}$ = 0.25. From Fig. 407, this *ratio* shows a heating value of 15,850 *B.t.u. per lb. of combustible.* The ratio of volatile to carbon in the second case = $^{40}/_{50}$ = 0.8. Fig. 407 shows this ratio to produce 13,900 *B.t.u. per lb. of combustible.* Now, the first coal is 16 + 64 = 80 *per cent. combustible,* whereas the second is 40 + 50 = 90 *per cent. combustible.* Hence, the *heating value of the first coal* = 0.8 × 15,850 = 12,680 *B.t.u. per pound.* Also, *the heating value of the second coal* = 0.9 × 13,900 = 12,510 *B.t.u. per pound.* Therefore, if only heating values are considered the first coal would be chosen.

4. The second sample has less water and ash than the first.

SOLUTIONS TO PROBLEMS ON DIVISION 14

COMBUSTION

1. By For. (329), *the weight of air per pound of fuel burned,* $\mathbf{W_A}$ = $3.036\,C\,\frac{N}{CO_2 \times CO} = 3.036 \times 0.8 \times \frac{84}{8 + 1}$ = 22.67 *lb.*

2. By For. (330), *the percentage of excess air above that which is theoretically required, X,* =

$$\left(\frac{N}{N - 3.782(0 - \tfrac{1}{2}CO)} - 1\right) \times 100 = \left(\frac{84}{84 - 3.782(7 - \tfrac{1}{2})} - 1\right) \times 100 = 41.3 \textit{ per cent.}$$

3. By For. (331), *the weight of dry fine gases per pound of coal burned,* $W_P = \left[\frac{11CO_2 + 8O + 7(CO + N)}{3(CO_2 + CO)}\right]C =$ $\left[\frac{11 \times 8 + 8 \times 7 + 7 \times (1 + 84)}{3 \times (8 + 1)}\right] \times 0.8 = \left[\frac{88 + 56 + 595}{27}\right] \times 0.8 =$ 21.90 *lb.*

4. By For. (334), *the heat lost for each pound of coal purned due to the unburned carbon monoxide.*

$$H_{CO} = 10{,}220 \times \frac{CO}{CO_2 + CO} \times O = 10{,}220 \times \frac{1}{8 + 1} \times 0.8 = 908 \text{ B.t.u.}$$

SOLUTIONS TO PROBLEMS ON DIVISION 15

STEAM POWER PLANTS

1. By For. (342), *the efficiency of the boiler, furnace and grate* = **E** = $\frac{Q_B}{H} = \frac{8{,}000}{11{,}450} = 0.698$, or 69.8 *per cent.*

2. From the steam tables (Table 394) it is found that the total heat of dry saturated steam at a pressure of 150 lb. per sq. in. gage, is 1,195 *B.t.u. per lb.* But since the eedwater was admitted to the boiler at a temperature of 210° F. each pound of feed water contained 210 − 32 = 178 *B.t.u.* Therefore, *the net heat which was absorbed by each pound of water in the boiler* = 1,195 − 178 = 1,017 *B.t.u.* For *each pound of coal fired,* 55,120 ÷ 5,350 = 10.30 *lb. of steam was formed.* Therefore, *for each pound of coal which was consumed, the boiler absorbed* 10.30 × 1,017 = 10,475 *B.t.u.* By For. (342), *the efficiency of the boiler, furnace and grate,* $\mathbf{E} = \frac{Q_B}{H} = \frac{10{,}475}{15{,}300} =$ 0.787 or 78.7 *per cent.*

3. *The length of stroke* = 22 ÷ 12 = 1.83 *ft.* The effective *piston area of the head-end* = (16 × 16 × 3.14 ÷ 4) = 201 *sq. in.* The effective *piston area of the crank-end* = 201 − (area of the piston rod) = 201 − (2 × 2 × 3.14 ÷ 4) = 201 − 3.14 = 197.86 *sq. in.* By For. (343) *the indicated horsepower developed in the head-end of the cylinder,* **P** =

$$\frac{PLAN}{33{,}000} = \frac{59 \times 1.83 \times 201 \times 200}{33{,}000} = 131.5 \text{ hp.}$$

By For. (343) the indicated horsepower developed in the crank-end of the cylinder, $\mathbf{P} = \frac{PLAN}{33{,}000} = \frac{59 \times 1.83 \times 197.86 \times 200}{33{,}000} = 129.4$ *hp.* By Sec. 504, *the total indicated horsepower* = 131.5 + 129.4 = 260.9 *hp.*

4. By Prob. 2, there was generated 55,120 lb. of steam during the 10 hr. period, or 55,120 ÷ 10 = 5,512 *lb. per hr.* If only 94 per cent. of this amount is consumed by the engine, *the engine consumption* = 5,512 × 0.94 = 5,181 *lb. of steam per hour.* From Table 394, the total heat of dry saturated steam at a pressure of 145 lb. per sq. in., gage, is 1,194.5 *B.t.u. per lb.* From Table 394, the heat of the liquid corresponding to the temperature of 220° F. is 188.1 *B.t.u. per lb.* By Prob. 3, the power developed within the engine cylinder was 260.9 hp. If 90 per cent. of this power is delivered to the shaft, *the brake horsepower* = 260.9 × 0.90 = 234.8 *hp.* By For. (344), *the thermal brake efficiency,*

$\mathbf{E} = \frac{2{,}545 \times P_B}{W_S(H - h)} = \frac{2{,}545 \times 234.8}{5{,}181 \times (1{,}194.5 - 188.1)} = \frac{597{,}566}{5{,}214{,}158} = 0.114$ or 11.4 *per cent.*

5. From the solution to Prob. 3, *the indicated horsepower was* 260.9 *i.hp.* From the solution to Prob. 4, *the steam consumption was* 5,181 *lb. per hr.* Therefore, by Sec. 507 *the water rate*, which is the number of pounds of steam required to develop one unit of energy or 1 i.hp., = 5,181 ÷ 260.9 = 19.8 *lb. of steam per indicated horsepower hour.*

6. By the solution to Prob. 2, *the total heat of the steam generated in the boiler was* 1,195 *B.t.u. per lb.* By For. (345), the fuel saving, $X = \frac{(T_2 - T_1)}{H - (T_1 - 32)} = \frac{(210 - 70)}{1{,}195 - (70 - 32)} = \frac{140}{1{,}157} = 0.121$ or 12.1 *per cent.*

7. By Prob. 3, the weight of coal consumed during the 10 hr. period was 5,350 *lb.* From the solution to Prob. 2, the total average indicated horsepower developed during the test period was 260.9. Therefore, the total energy in horsepower-hours developed within the engine cylinder for the 10-hr. period = 10 × 260.9 = 2,609 hp.-hr. By For (346), the *overall efficiency*, $W = \frac{W_T}{e} = \frac{5{,}350}{2{,}609} = 2.05$ *lb. of coal per indicated horsepower-hour.* From Prob. 2, the heating value of the coal was 13,300 B.t.u. per lb. By For. (347), *the overall efficiency*, $Q = H \times W = 13{,}300 \times 2.05 = 27{,}265$ *B.t.u. per indicated horsepower-hour.* By For. (349) *the overall thermal efficiency*, $E_T = \frac{2{,}545}{27{,}265} = 9.3$ *per cent.*

8. From Fig. 437, the average height of the indicator diagram is 0.723 *in.* Since the scale of the spring is 50, the *mean effective pressure* = 0.723 × 50 = 36.15 *lb. per sq. in.*

SOLUTIONS TO PROBLEMS ON DIVISION 16

INTERNAL-COMBUSTION-ENGINE POWER PLANTS

1. The area of the piston $= \frac{\pi d^2}{4} = \frac{3.14 \times (16 \times 16)}{4} = 201$ *sq. in.* A Diesel engine running at 200 r.p.m. will have: 200 ÷ 2 = 100 *work strokes per min.* By For. (351), *the indicated horsepower for each cylinder*, $P = \frac{PLAN}{33{,}000} = \frac{106 \times 2 \times 201 \times 100}{33{,}000} = 129.1$ hp. Since the engine has 4 cylinders, *the total indicated horsepower* = 4 × 129.1 = 516.4 *hp.*

2. By For. (352), *the thermal brake efficiency* $= \frac{2{,}545 \times 140}{15{,}400 \times 128} = \frac{356{,}300}{1{,}971{,}200} = 0.180$, or 18 *per cent.*

3. By For. (353), *the brake horsepower:* $P_B = \left(\frac{d^2LN}{k_1} - k_2\right)k_3$. For this engine, $d^2 = 7.5 \times 7.5 = 56.25$. $L = 12$. $N = 300$. $k_3 = 1$. By Item 5 under For. (353), $k_1 = 16{,}400$ and $k_2 = 0.5$. Therefore, *the brakehorsepower* $= \left(\frac{56.25 \times 12 \times 300}{16{,}400} - 0.5\right) \times 1 = 12.3 - 0.5 =$ 11.8 *hp.* Such an engine would probably be rated at 12 hp.

SOLUTIONS TO PROBLEMS ON DIVISION 17

BUILDING WARMING

1. *The total exposed wall area,* $A = (14 + 18) \times 10 = 320$ *sq. ft. The volume of the room,* $V = 14 \times 18 \times 10 = 2{,}520$ *cu. ft.*

By Table 569, $N = 2$. By For. (361,) *the total heat loss,* $Q_T = (A_G + 0.25A + 0.02NV)T = (100 + 0.25 \times 320 + 0.02 \times 2 \times 2{,}520) \times 70 =$ 19,600 *B.t.u. per hr. for a south room,* but since the room has a southeast exposure, this value should (Table 571) be multiplied by 1.05. Or, $1.05 \times 19{,}600 = 20{,}580$ *B.t.u. per hr.* is lost.

2. By Sec. 573, 0.02 B.t.u. will raise the temperature of 1 cu. ft. of air 1° F. Therefore, *the quantity of heat required to raise* 30,000 *cu. ft. of air* 70° *F.* $= 0.02 \times 30{,}000 \times 70 = 42{,}000$ *B.t.u.*

3. The allowance should be based on a 0-to-70° F. temperature raise By For. (355), *the allowance* $= Q_A = 2{,}520n = 2{,}520 \times 150 = 378{,}000$ *B.t.u. per hr.*

4. *The cubical capacity of the room* $= 20 \times 20 \times 10 = 4{,}000$ *cu. ft.* By Table 569, about 2 complete changes of air will occur per hour, or. $2 \times 4{,}000 = 8{,}000$ *cu. ft. of fresh air,* which will be supplied per hour by infiltration. This will provide ventilation for: $8{,}000 \div 1{,}800$, or 4 *persons.*

5. By Sec. 559, *the quantity of heat given off by* 40 *persons* $= 40 \times 400 = 16{,}000$ *B.t.u. per hr.*

The rate of heat emission of the line shaft $= 75 \times 2{,}545 = 190{,}950$ *B.t.u. per hr.*

By Sec. 576, *the rate of heat emission of the electric lamps* $= 16 \times 100 \times 3.415 = 5{,}464$ *B.t.u. per hr.*

The total heat emitted per hour within the room is, then, $= 16{,}000 + 190{,}950 + 5{,}464 = 212{,}414$ *B.t.u.*

6. *The quantity of coal required, if the furnace was* 100 *per cent. efficient would be:* $50{,}000 \div 11{,}500 = 4.35$ *lb. per hr.* Since only 55 per cent. of the heat of the coal reaches the room, *the coal consumption must be:* $4.35 \div 0.55 = 7.9$ *lb. per hr.*

7. By Table 394, steam at 2.5 lb. per sq. in. gage has a temperature of about 220° F. By Fig. 517, K, *for a 4-column* 44-in. *radiator,* = 1.4 B.t.u. per sq. ft. per hour per degree temperature difference.

By For. (362), *the required radiator area,* $A = \frac{Q_T}{K(T_2 - T_1)} =$

$$\frac{158{,}000}{1.4 \times (220 - 70)} = 752 \text{ sq. ft}$$

8. By For. (366), *the requisite grate area,* $A = \frac{1.25Q_T}{HWE} =$

$$\frac{1.25 \times 158{,}000}{12{,}500 \times 7 \times 0.69} = 3.27 \text{ sq. ft.}$$

9. By Sec. 601, 1 boiler hp. is equivalent to 33,479 *B.t.u. per hr.* Therefore, *the boiler should have a rating of* $(1.25 \times 158{,}000) \div 33{,}479 = 5.9$ boiler hp.

10. *By For.* 367, *the volume of air required to warm the room,*

$$V = \frac{55Q_T}{(T_1 - T_2)} = \frac{55 \times 70{,}000}{135 - 65} = 55{,}000 \textit{ cu. ft. per hr.}$$

11. *The quantity of air recirculated,* $V_C = 0.20 \times 55{,}000 = 11{,}000$ *cu. ft. per hr. The quantity of air brought in from the outside,* $V_O = 55{,}000 - 11{,}000 = 44{,}000$ *cu. ft. per hour.* By For. (371), *the ratio,* $X = \dfrac{(T_F - T_O)V_O + (T_F - T_2)V_C}{(V_O + V_C)(T_1 - T_2)} =$

$$\frac{(180 - 0) \times 44{,}000 + (180 - 65) \times 11{,}000}{(44{,}000 + 11{,}000) \times (135 - 65)} = 2.38.$$

12. By Prob. 11, $X = 2.38$. By For. (372), *the grate area,* $A = \dfrac{XQ_T}{\mathbf{HWE}} = \dfrac{2.38 \times 70{,}000}{11{,}000 \times 8 \times 0.65} = 2.9$ *sq. ft.*

SOLUTIONS TO PROBLEMS ON DIVISION 18

REFRIGERATION

1. The lowest temperature that can be obtained by surface evaporation is the wet-bulb temperature. From the psychrometric chart, Fig. 323, Div. 10, the wet-bulb temperature can be found when two properties are given, such as dry-bulb temperature and relative humidity. The point of intersection of the dry-bulb temperature line and the relative humidity line is found and then the wet-bulb temperature is read on the inclined "Wet-bulb Temperature" line. Thus for this problem, the intersection of the 70° F. dry-bulb temperature line and the 0.40 relative humidity line is determined. Following along the inclined line to the left, the wet-bulb temperature is found to be 55.8° F. Thus the lowest temperature that can be obtained by surface evaporation is 55.8° F.

2. *Heat absorbed in* 24 *hr.* $= (520 \times 0.7 + 900)24 = (364 + 900)24 = 1{,}264 \times 24 = 30{,}336$ *B.t.u.* Since 1 lb. of ice will absorb 144 B.t.u., *the ice required in* 24 *hr.* $= \dfrac{30{,}336}{144} = 210.6$ *lb.*

3. By For. (236), $T_2 = T_1\left(\dfrac{P_2}{P_1}\right)^{\frac{k-1}{k}}$, $T_2 = (460 + 100)\left(\dfrac{40}{100}\right)^{\frac{1.4-1}{1.4}} = 560 \times 0.4^{0.285} = 560 \times 0.771 = 431.7°$ *F. abs.* or $-28.3°$ *F.*

4. The pressure on the water must be the vapor pressure corresponding to the boiling temperature. The vapor pressure corresponding to the boiling temperature of 50° F. can be found by interpolating the values given for 32° F. and 59° F. in Table 394. Thus, *the pressure that must be imposed on the water for it to boil at* 50° *F.* $= 0.088{,}6 + \left[(0.247{,}2 - 0.088{,}6) \times \dfrac{(50 - 32)}{(59 - 32)}\right] = 0.088{,}6 + \left(\dfrac{0.158{,}6 \times 18}{27}\right) = 0.088{,}6 + 0.105{,}7 = 0.194{,}3$ *lb. per sq. in. abs.*

5. Heat absorbed by 1 lb. of anhydrous ammonia is equal to the difference between the total heat of the saturated vapor at 29.95 lb. per sq. in. abs. and the heat of the liquid at 80° F. From Table 400, the total heat of dry saturated ammonia vapor at 29.95 lb. per sq. in. abs. is found to be 538.5 B.t.u. per lb. The heat of the liquid ammonia at 80° F. is found from the same table to be 53.6 B.t.u. per lb. Then, *the heat absorbed by* 1 *lb. of anhydrous ammonia* = 538.5 − 53.6 = 484.9 *B.t.u. Ammonia vaporized per hour* = $\frac{10,000}{484.9}$ = 20.65 *lb. per hour.*

6. The minimum pressure in the condenser is that which corresponds to a boiling temperature of 70° F. From Table 400 the pressure under which ammonia boils at 70° F. is found to be 129.2 *lb. per sq. in. abs.*

7. *Heat absorbed* = *Heat required to cool water to* 32° + *Heat required to freeze water into ice* + *Heat required to cool ice* = (70 − 32) + 144 + 0.5(32 − 20) = 178 *B.t.u.*

8. *Heat absorbed in* 24 *hr.* = 260 × 2,000 × 5 = 2,600,000 *B.t.u.* By definition, 1 *ton refrigeration* = 288,000 *B.t.u. per* 24 *hr.* Then *capacity required* = $\frac{2,600,000}{288,000}$ = 9.04 *tons refrigeration.*

9. *Coefficient of performance* = $\frac{\textit{Heat extracted from cold body}}{\textit{Indicated work of compressor}}$ = $\frac{288,000}{2 \times (33,000 \div 778) \times 60 \times 24}$ = 2.36.

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